IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received December 22, 2019, accepted January 7, 2020, date of publication January 21, 2020, date of current version January 29, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2968461

A Comprehensive Review of Power Flow Controllers in Interconnected Power System Networks

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This work was supported in part by the Qatar National Library, Doha, Qatar.

ABSTRACT Energy security is one of the most crucial factor in the development of any nation. Interconnections among different power system networks are made to lower the overall price of power generation as well as enhance the reliability and the security of electric power supply. Different types of interconnection technologies are employed, such as AC interconnections, DC interconnections, synchronous interconnections, and asynchronous interconnections. It is necessary to control the power flow between the interconnected electric power networks. The power flow controllers are used to (i) enhance the operational flexibility and controllability of the electric power system networks, (ii) improve the system stability and (iii) accomplish better utilization of existing power transmission systems. These controllers can be built using power electronic devices, electromechanical devices or the hybrid of these devices. In this paper, control techniques for power system networks are discussed. It includes both centralized and decentralized control techniques for power system networks. This paper also presents a comprehensive review of HVDC interconnections, asynchronous AC interconnections, synchronous AC interconnections and different types of power flow controllers used in these interconnections. Moreover, some important and multivariable flexible AC transmission system (FACTS) devices such as UPFC and IPFC are also discussed with their merits and limitations. Finally, a new asynchronous AC link called flexible asynchronous AC link (FASAL) system is also described in detail. At last, a summary of the comparative analysis of power system link and power flow controllers is given based on recent publications. More than 400 research articles and papers on the topic of power transfer control are covered in this review and appended for a quick reference.

INDEX TERMS Power system interconnections, asynchronous link, synchronous link, HVDC link, LCC-HVDC system, VSC-HVDC system, PST, PAR, Sen transformers, controllable network transformer, FACTS controllers, UPFC, IPFC, virtual synchronous machines (VSM), matrix converters, variable frequency transformer (VFT), flexible asynchronous AC link (FASAL).

LIST OF ABBREVIATIONS

AC	Alternating current
AEP	American electric power
C-BBC	Current DC link back-to-back converter
CEPCO	Chubu electric power company
CF	Commutation failure
CMC	Conventional matrix converter
CNT	Controllable network transformer
D	Duty cycle
DC	Direct current
DFIM	Doubly fed induction machine
DG	Distributed generator
DMC	Direct matrix converter
DSP	Digital signal processor
DVQS	Dual virtual quadrature sources
EHV	Extra high voltage

The associate editor coordinating the review of this manuscript and approving it for publication was Ahmad Elkhateb.

EHVAC	Extra high voltage AC
eVSM	Enhanced virtual synchronous machine
F3EC	Fundamental frequency front end converter
FACTS	Flexible AC transmission system
FASAL	Flexible asynchronous AC link
FC-TCR	Fixed capacitor thyristor controlled reactor
FRT	Fault ride through
GTO	Gate turn-off thyristors
HAF	Hybrid active filter
HIMC	Hybrid Indirect matrix converter
HVDC	High voltage direct current
IHUPFC	Improved hybrid unified power flow controller
IGBT	Insulated gate bipolar transistors
IMC	Indirect matrix converter
INELFE	INterconexion ELectrica Francia-Espana
IPFC	Inline power flow controller
LCC	Line commutated converter
LTC	Load tap-changers
MC	Matrix converter
MTDC	Multi-terminal HVDC
OLTC	On-load tap-changers
P	Active power
PAR	Phase angle regulator
PF	Power factor
PFC	Power flow controller
PID	Proportional integral derivative
PLL	Phase locked loop
PMU	Phasor measurement unit
PSN	Power system network
PST	Phase shifting transformer
PWM	Pulse width modulation
Q	Reactive power
QB	Quadrature booster
RB	Reverse-blocking
RES	Renewable energy resources
RPFC	Rotary power flow controller
RPST	Rotary phase shifting transformer
SC	Synchronous condenser
SJ	Superjunction
SM	Synchronous machine
SMC	Sparse matrix converter
SOC	State of charge
SPWM	Sinusoidal pulse width modulation
SSR	Sub-synchronous resonance
SSSC	Static synchronous series compensator
ST	Sen transformer
STATCOM	Static synchronous compensator
SVG	Static VAR generators
TCR	Thyristor controlled reactor
TCSC	Thyristor controlled series capacitor
THD	Total harmonic distortion
TSC	Thyristor switched capacitor
T–SC	T–Source converter
TSSC	Thyristor switched series capacitor
UHV	Ultra high voltage
UPFC	Unified power flow controller
USMC	Ultra sparse matrix converter
VAR	Volt-ampere reactive
V-BBC	Voltage DC link back-to-back converter
VFT	Variable frequency transformer
VR	Voltage regulator
VR-VSI	VIENNA Rectifier with Voltage Source Inverter
VSC	Voltage source converter
VSG	Virtual synchronous generator
VSM	Virtual synchronous machine
VSMC	Very sparse matrix converters
VTR	Voltage transfer ratio
WRIM	Wound rotor induction motor
ZSC	Z–Source converter

I. INTRODUCTION

The electric power system around the globe has been evolved as an isolated system. They are built to transmit electrical power from a centralized power generating station to a vast area distributed load. The power flow was unidirectional from a centralized generating station to a wide area distributed loads [1]. Today, the interconnections between adjacent electric power system make a power network which permits electric utilities to operate reliably and economically [2]. Interconnections allow to acquire the benefit of a diversified generation mix, fuel prices and exploit the diverse loads which exist between neighbouring power system networks. Therefore, the electricity demand can now be fulfilled at a lower price and can also ensure the security and the reliability of the power system network [3]. Moreover, the interconnection of electric power networks reduces the generating reserve capacity needs in each system. This reduces the investments in generating capacity or at least delays the requirement of adding new capacity [4]. Further, the liberalization of the electric power market also assists in interconnecting electric power networks. It permits the commercialization of power among different regions and countries [5].

The rise in electricity demand is due to the continuous and rapid growth of economic development. The increase in load demand, rising level of renewable energy penetration, and restricted transmission infrastructure investments are some of the reasons for the requirement of a smart controllable grid. In order to ensure reliable and cost-effective power supply, interconnections are made between neighbouring electric networks through the tie-lines. It provides an alternative path of power flow in case of contingencies. As a result, most of the power system networks usually shifts from a radial to a meshed network [6]. One of the main issues encountered by the utilities is poor controllability of tie-lines between the electric power system networks. At present, utilities have limited control over the power flow via these tie-lines. The tie-lines have a susceptibility of getting overloaded and tripped under the influence of disturbances and contingencies. This leads to the change in the direction of power flow, i.e., the flow of power becomes opposite to the network support requirement [7].

The controllability of power flow through the transmission lines is being increased without compromising its reliability. This is achieved by increasing the utilization of the system using power flow controllers. Different types of power flow controllers have already been suggested by the researchers [7]–[10]. The power flow can be boost with the help of power flow controlling devices in a meshed network. This is done by increasing the usage of parallel lightly loaded lines. Moreover, it prevents the overloading of highly loaded lines [11], [12].

Power flow in a transmission line is inversely proportional to its line reactance. The power flow control has been practiced using a variable inductive and variable capacitive reactance in series with the line [13]. The nature of the transmission line is considered to be inductive. The power flow decreases by increasing the effective line reactance by the use of a series-connected inductor between sending and receiving ends. Similarly, the power flow increases by reducing the overall line reactances through a series-connected capacitor between its two ends [14].

The traditional power flow controllers include the voltage regulator (VR), the phase angle regulator (PAR), and the phase-shifting transformers (PST). It uses a transformer and mechanical load tap-changers (LTCs). However, the time response of this system is slow.

Recently, extensive attention is paid by the utility engineers and researchers on interconnection technologies and power flow controllers due to the formation of micro-grids, integration of renewables to the utility grids, the interconnection of regional grids [15]–[17]. There is a need for detailed review of interconnection technologies and power flow controllers. Hence, in this paper, a detailed and comprehensive review on the topic is presented.

The power system networks (grids) interconnections can be broadly categorized as AC link and DC link (HVDC link). The AC interconnection is preferred because of its dominant mode of generation, transmission, distribution, and utilization. These interconnections may be synchronous or asynchronous depending upon the situation and operating parameters of the grids. The methods of asynchronous ac link and power flow control mechanisms are described in detail with their merits and demerits. The power flow controllers used in synchronous ac link are also discussed in detail. More than 400 published articles are reviewed and classified into two major categories, such as DC interconnections and AC interconnections. These are further classified into several subcategories as shown in Fig. 1.

The remaining paper is arranged in the following manner. In Section II, control techniques for power system networks are discussed which include both centralized and decentralized control techniques. In Section III, asynchronous HVDC interconnection based on line-commutated converter (LCC) and voltage source converters (VSC) topologies has been described. Some of the existing worldwide projects based on the aforementioned topologies are also presented. In Section IV, a brief overview of AC interconnection

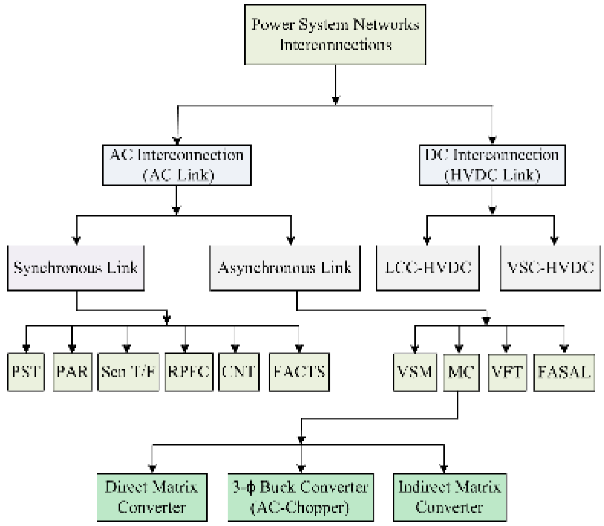

FIGURE 1. Classification of power system network interconnections and power flow controllers.

and its classification based on operating parameters has been discussed. Further, various types of power flow controllers used in synchronous interconnections are presented in Section V. Moreover, the FACTS devices which include UPFC and IPFC are discussed in detail with their merits and limitations in Section VI. Then, various methods for AC asynchronous interconnection such as virtual synchronous machines (VSM), matrix converter (MC), variable frequency transformer (VFT) and flexible asynchronous AC link (FASAL) are explored in Section VII. A summary of the comparative analysis of power system link and power flow controllers is presented in Section VIII. Finally, a brief conclusion is made in Section IX.

II. CONTROL TECHNIQUES FOR POWER SYSTEM NETWORK

Traditionally, the massive scale of the power system networks was efficiently controlled by the open-loop scheme. Here, simple control techniques with relatively slower responses satisfy the supply and demand requirement of the power system network in real-time. However, the advancement of different sources of power generation (e.g., renewable energy, small scale distributed generator, etc.) and its integration to the existing power system network has brought challenges for the controller. The reason for the same is because the renewable source of energy is unreliable and often leads to unpredicted fluctuation in the supply side of the power system network. Therefore, there is a consistent requirement of fast and efficient control action [18]. The control in the power system network can be broadly classified into two categories: Centralized and decentralized (non-centralized).

A. CENTRALIZED CONTROL

The centralized control system consists of a single controller for the entire power system network. The objective of this controller is to carry out the following set of operations within a time sample: evaluate all the output variables of the power system, compute the control command using an appropriate control algorithm, and implement this computed control through all the actuators of the power system network. The power system network is a vast system, both in the sense of graphically and computationally. It is practically a tough job to implement any advanced control scheme for such an extensive network with a single control command [19]. This is one of the reasons why the researchers have shown the least interest in the control design of the centralized system.

B. DECENTRALIZED CONTROL TECHNIQUES

The decentralized control system comprises of a multivariable set of systems which works for the accomplishment of a global objective task by cooperating with many controllers of the entire system. Every individual controller computes a subset of input command separately under no or limited communication with the other controllers. The advantage of decentralized control system over centralized control system are: (i) The decentralized control does not require a high processing computational unit for the execution of global complex control schemes for the whole power system network dynamics. Instead, multiple straightforward control commands are evaluated using several basic units, which are also cost-efficient. (ii) The measurements of the output variable and the control commands do not have to be transmitted to a single processing unit. The global control task can be achieved with a minimal exchange of information between the spatially dispersed units of the system [20].

A constructive review of the recent advancement of voltage control techniques for the distributed and decentralized power networks is presented in [21]. This paper demonstrates different control models and methodologies which have been implemented for the decentralized system. Further, the authors have also addressed future research and its use in industrial applications. In a brief, some of the control techniques which have been implemented in the decentralized power system are: model predictive control [18]–[20], neural networks based load frequency control [22], PID based automatic generation control [23]. Optimization-based control schemes have also been employed in the designing of decentralized controller, e.g., non-linear programming (NLP) [24], genetic algorithm (GA) [25], particle swarm optimization (PSO) algorithm [26], and references therein.

III. HVDC INTERCONNECTION (LINK)

HVDC link is used for asynchronous interconnections of two power system networks (grids). The parameters (voltage and frequency) of both the grids may be the same or different. It controls the real power flow between these grids, which requires reactive power support. The HVDC link is also used to integrate wind energy system to the utility grids [27], [28]. A basic simplified HVDC link is shown in Fig. 2 [29]. In general, an HVDC system consists of a DC line and converter stations at both the sending and receiving ends. The converter station mainly comprises of converter transformers,

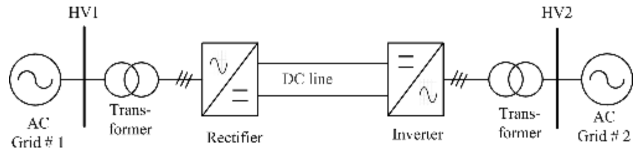

FIGURE 2. A basic simplified HVDC transmission link.

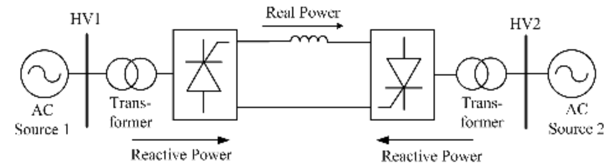

FIGURE 3. Simplified diagram of LCC-HVDC system.

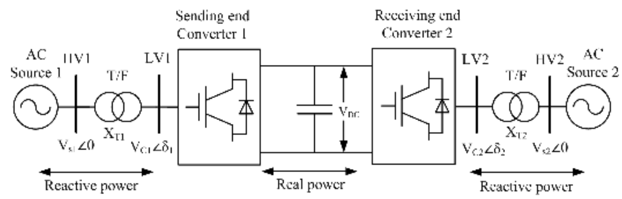

FIGURE 4. Schematics of VSC-HVDC system.

converter valves, AC filters, DC filters, smoothing reactors, overvoltage protection schemes, controls systems, and other devices [30]–[34]. The two main converter topologies are being employed in the present HVDC transmission systems which are as follows.

A. HVDC BASED ON LINE-COMMUTATED CONVERTER SYSTEM

The conventional HVDC system is the line-commutated converter based HVDC (LCC-HVDC) or current source converter based HVDC (CSC-HVDC) which uses thyristors as shown in Fig. 3. This HVDC topology is well established for long-distance and bulk power transmission systems. For example high power, long distance projects are: (i) Itaipu (in Brazil) HVDC transmission system having 6300 MW, voltage ±600 kV, approximately 800 km, uses two bipolar dc lines [35], (ii) Xiangjiaba hydropower plant to Shanghai HVDC system having 6400 MW, ±800 kV, 2000 km, uses one single bipolar DC line [36], (iii) Southern Hami-Zhengzhou UHVDC Transmission Project, 8000 MW, ±800kV, 2210 km, (iv) Zhundong-Sichuan UHVDC transmission project, 10000 MW, ±1100 kV, 2600 km and (v) Agra - Bishwanath Chariali HVDC Line, 6000 MW, ±800kV, 1728 km [37].

B. HVDC BASED ON VOLTAGE SOURCE CONVERTERS SYSTEM

The recent HVDC system is the voltage source converters based HVDC (VSC-HVDC) that uses GTOs or IGBTs as shown in Fig. 4 [38]. It is generally used for medium power and short distance power transmission. The few recent VSC-HVDC projects are: (i) Trans Bay Cable Project (USA),

±200 kV, 400 MW, 85 km [39], (ii) East West Interconnector (EWIC) Project (UK), ±200 kV, 500 MW, 261 km [40], (iii) INELFE (France), ±320 kV, 1000 MW, 65 km [41] and (iv) Skagerrak 4 (Norway), ±500kV, 700 MW, 240 km [42].

The real power and the reactive power transmission between the AC bus and the converter depend on the magnitude of the voltages at both sides of the transformer, the phase angle δ_1 between these voltages and the reactance of the transformer X_{T1}. The real and the reactive power transmission between the AC bus and the converter AC terminals can be expressed with reference to Fig. 4 as presented in [43].

The real and the reactive power at the sending end is expressed as

$$P_S = \frac{V_{S1}V_{C1}}{X_{T1}} \sin \delta_1 \tag{1}$$

$$Q_S = \frac{V_{S1}^2}{X_{T1}} - \frac{V_{S1}V_{C1}}{X_{T1}} \cos \delta_1 \tag{2}$$

Similarly, the real and the reactive power at the receiving end is obtained as

$$P_R = \frac{V_{S2}V_{C2}}{X_{T2}} \sin \delta_2 \tag{3}$$

$$Q_R = -\frac{V_{S2}^2}{X_{T2}} + \frac{V_{S2}V_{C2}}{X_{T2}} \cos \delta_2 \tag{4}$$

The power transmission is regulated using sinusoidal pulse width modulation (SPWM) approach by controlling the phase, magnitude, and the fundamental frequency component of the converter's output AC voltages V_{C1} and V_{C2}.

However, requirements of filter banks for harmonics filtering, coordinated control, and compensation of reactive power leads the HVDC system to become more complicated. Whenever, the low rating AC power network is connected on either side of the HVDC link, it reduces the performance [44], [45]. Moreover, installation of the HVDC system requires large space and high initial cost for the placement of HV switches and filter banks [46].

Moreover, the LCC-HVDC cannot feed the power to the passive networks without the generation of local power [47], [48]. Furthermore, LCC-HVDC system faces the problem of commutation failure even when there is a 10%-14% dip in the voltage level of inverter AC bus [49]–[51]. The issues of commutation failure (CF) in LCC-HVDC system can be minimized by the application of synchronous condenser (SC), static synchronous compensators (STATCOM) or VSC-based HVDC [52]–[54]. However, these solutions have higher capital costs required for additional apparatus to CF mitigation [50]. The VSC-HVDC system can feed power to the passive networks without local power generation [55], [56]. However, a VSC-based HVDC transmission has the demerit of high capital cost and significant power loss than a LCC-HVDC system [47].

IV. AC INTERCONNECTIONS

The AC power generation is the traditional and dominant mode of power generation, transmission, distribution, and utilization of electrical energy. Therefore, an AC link is the most widely accepted technique of interconnections of two AC power system networks. There are two ways of interconnection of the AC power system networks using AC links which are discussed below.

A. SYNCHRONOUS AC INTERCONNECTIONS

The conventional method of interconnection is the synchronous interconnections. In this method, the two synchronous power networks (having the same frequency and same voltage level) are connected with an AC link line, which is called the tie line. The power flow control through these link lines and between the interconnected power system networks is achieved by the use of power flow control devices. These devices (controllers) are discussed in the next section.

B. ASYNCHRONOUS AC INTERCONNECTIONS

The majority of the power transmission system is using extra high voltage alternating current (EHVAC), and it is very successful. Therefore, the interconnection of systems with different operating characteristics (voltages and frequencies) AC asynchronous interconnection is preferred. In the next section, various AC asynchronous interconnections technologies have been described in detail.

V. POWER FLOW CONTROLLERS IN SYNCHRONOUS AC INTERCONNECTIONS

A. PHASE-SHIFTING TRANSFORMERS

The voltage and phase angle regulating transformers are used to control the real power flow in parallel transmission lines and interconnected electric power system networks. These phase and voltage regulating transformers are also called phase-shifting transformer (PST), phase angle regulator (PAR), phase shifter and quadrature booster (QB) [57]–[60]. The voltage and phase angle regulation is realized by adding an in-phase or a quadrature component to the bus voltage. Therefore, synchronous in-phase voltage source having controllable magnitude $\pm\Delta V$ in series with the AC bus voltages cause the voltage regulation. The required voltage regulation is obtained by a three-phase, auto-transformer usually called a regulating or excitation transformer as shown in Fig. 5(a) [61]. It can be seen that the injected voltages $\pm\Delta V_a$, $\pm\Delta V_b$, and $\pm\Delta V_c$ are in phase with the line to neutral voltages V_a, V_b and V_c, respectively (Fig. 5(b)).

Fig. 6 describes the PST as a series reactance along with a phase angle shift. The regulation of power through the transmission line is controlled by regulating the angle α, which in turn changes the existing angle δ. The power transferring capability of PST is within specified limits. The active power transfer over a transmission line is expressed as [62]:

$$P = \frac{V_S V_R}{X_L + X_{PST}} \sin(\delta + \alpha) \tag{5}$$

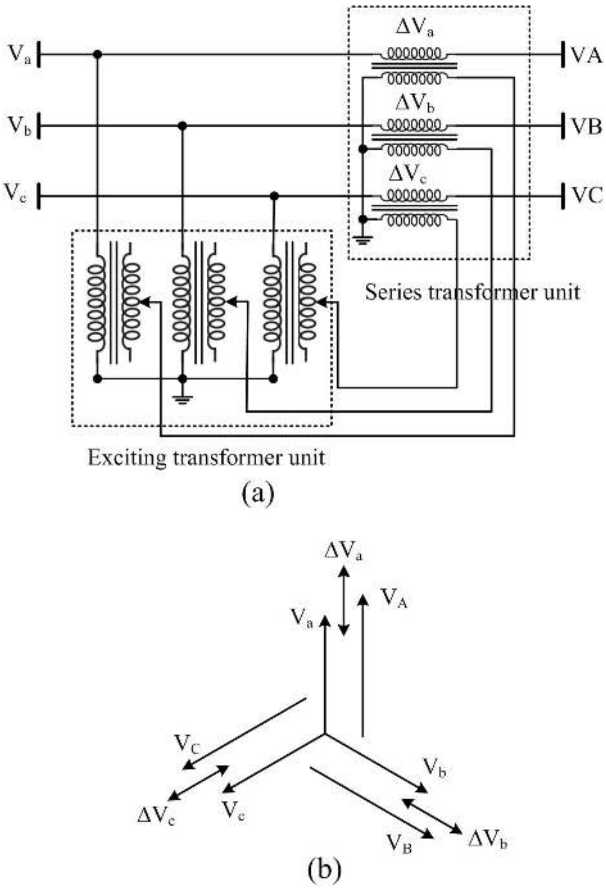

FIGURE 5. Voltage regulator. (a) simplified circuit diagram. (b) phasor diagram.

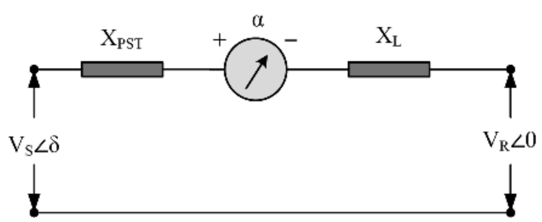

FIGURE 6. Transmission line model with a PST.

where X_L and X_{PST} are the line reactance and the PST leakage reactance, respectively.

The PSTs have different winding configurations based on the rated voltage, power output, and the amount of phase shift. The main available configurations are direct, indirect, symmetrical, and asymmetrical. The direct-asymmetrical PST configuration is shown in Fig. 7(a). It consists of a delta-connected exciting unit and regulating windings are wound on the same phase core limb. Each regulating winding comprises of a tap changer (T_A, T_B and T_C) and a selector switch [63]. In this configuration, quadrature voltage with variable magnitude, ΔV_{PST} is added to the input voltage, and a phase shift (α) appears between the input and the output terminal voltages as shown in Fig. 7(b). The change in the direction of the phase shift is controlled by utilizing switches. Hence, the magnitude of power flow in the line is regulated.

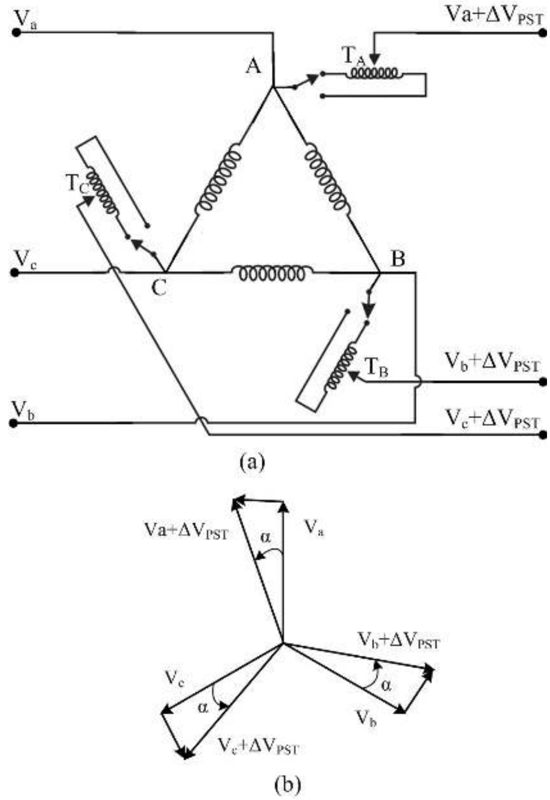

FIGURE 7. Direct-asymmetrical PST. (a) simplified circuit diagram. (b) phasor diagram

The PSTs can provide discrete phase shift, continuously variable phase shift, or a combination of the both. It may also be designed to control magnitude as well as phase angle. Discrete phase shifters normally provide settings for a plus-or-minus fixed value 9° and zero [57], [64].

Present days, high dissemination of distributed generation (DG) in the existing power system network leads to recurrent voltage fluctuations and overvoltages [65], [66]. An on-load tap-changers (OLTC) is used for the variable phase shift. Number of tapings are provided in OLTC to achieve any desired phase angle [67], [68]. On-load tap changing transformers allow voltages to be maintained at desired levels despite load changes. There are three types of OLTC available such as mechanical tap changers, power electronic assisted tap changers, and power electronic tap changers [69], [70].

Traditional OLTC voltage regulators are developed using mechanical tap switches, and it can perform under load conditions. However, due to the arching phenomenon in the tap changing, the mechanical switches experience regular wear and tear. Furthermore, in cases of frequent voltage variation due to DG penetration in the distribution system, the wear and tear are more severe [71], [72].

The application of power electronic devices has reduced the shortcomings of the mechanical switches. The power electronic devices in conjunction with PST and PAR uses semiconductor devices for the tap changing operations and

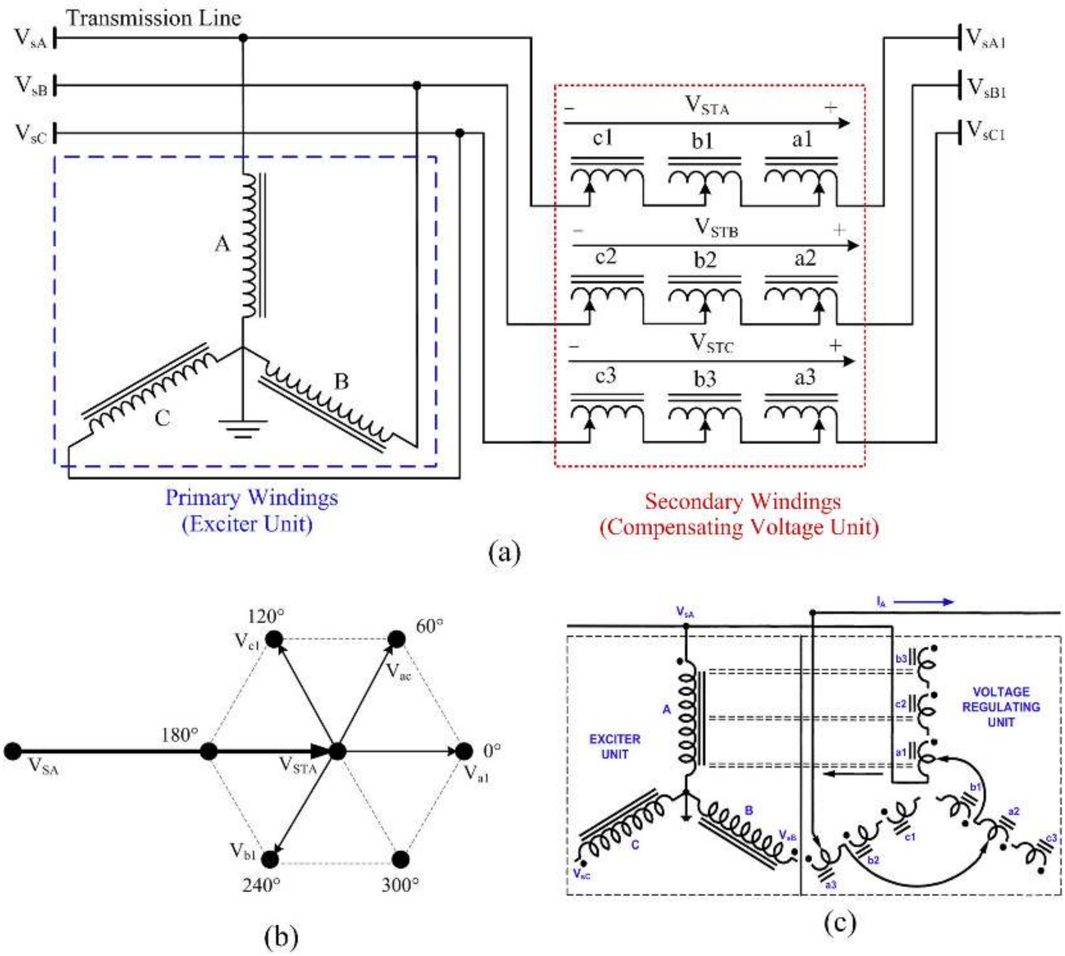

FIGURE 8. Sen Transformer. (a) Basic transformer configuration. (b) Output voltage phasor V_{STA}. (c) arrangements of primary and secondary windings.

hence avoids the arching phenomenon while tap changing process. [73]–[76]. The semiconductor-mechanical hybrid switch tap-changers called power-electronic-assisted tap changers, uses mechanical switches during the steady state whereas the semiconductor switches are used for the tap changing. It reduces losses and offers an arc-free tap-changing process [77], [78].

However, power electronics assisted tap changers also have limitations, such as the issues of harmonics, the vulnerability of rapid bypass for grid disturbances, higher steady-state losses, and small overload capacity [79].

B. SEN TRANSFORMER

The sen transformer (ST) is a combination of the phase angle regulators and load tap-changers. Figure 8 (a) shows the ST configuration which is connected to the sending end of the transmission line [80], [81]. The ST is a single core 3-phase transformer having star-connected primary winding and 9 secondary windings. In this transformer, the magnetic link is shared between primary and secondary windings. Three-phase voltages (V_{sA}, V_{sB}, and V_{sC}) is supplied in shunt to 3 primary windings (A, B, and C) having single-core, star-connected and placed on each limb of a three-limb. Three induced voltages (V_{STA}, V_{STB}, and V_{STC}) are generated for each phase (Fig. 8 (a)). Three windings are placed on three different limbs. One winding of each limb is connected in series for each phase. The sending-end voltages are changed from V_{sA}, V_{sB}, and V_{sC} to V_{sA1}, V_{sB1}, and V_{sC1} which are given by

$$\begin{aligned} V_{sA1} &= V_{sA} + V_{STA} = V_{sA} + V_{a1} + V_{b1} + V_{c1} \\ V_{sB1} &= V_{sB} + V_{STB} = V_{sB} + V_{a2} + V_{b2} + V_{c2} \\ V_{sC1} &= V_{sC} + V_{STC} = V_{sC} + V_{a3} + V_{b3} + V_{c3} \end{aligned} \tag{6}$$

The active number of turns in the secondary windings is varied with the help of tap-changers. The voltage-regulating unit consists of 9 secondary windings ($a1$, $c2$, and $b3$ on the core of phase-A, $b1$, $a2$, and $c3$ on the core of phase-B, and $c1$, $b2$, and $a3$ on the core of phase-C) as shown in Fig. 8 (c). Therefore, the resultant voltage becomes the function of varying magnitude and phase angle within the range of 0° to 360° (Fig. 8 (b)). The compensating voltage in any phase is determined by phasor sum of the voltages induced in a 3-phase winding set ($a1$, $a2$, and $a3$ for connection in phase-A, $b1$, $b2$, and

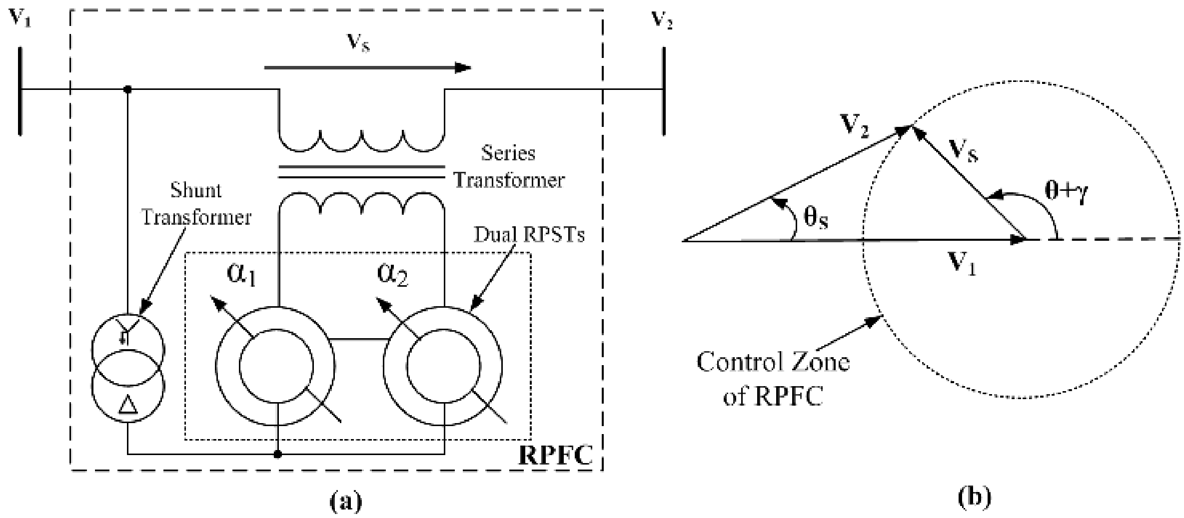

FIGURE 9. Rotary Power Flow Controller. (a) Simplified circuit diagram. (b) The associated voltage phasor diagram.

$b3$ for connection in phase-B, and $c1$, $c2$, and $c3$ for connection in phase-C) as shown in Fig. 8 (a). The in-phase component of the compensating voltage is modified for voltage magnitude compensation for each phase. For example, the compensating voltage of phase-A, V_{STA} is shown in Fig. 8 (b). The hexagonal representation shows that the output voltages and phase angle ρ_{ST}, which ST can provide. By modifying the number of turns of $a1$, the voltage (magnitude) of phase-A can be changed. Moreover, for out-of-phase compensation, the number of turns in $c2$ and $b3$ is adjusted accordingly [82], [83].

Independent and bidirectional active power and reactive power flow control are achieved by ST with the help of a transformer and on-load tap changers. The control strategy for tap changing and real-time simulation of ST have also been proposed in [84]–[86]. The ST reduces the device cost and losses significantly as compared to the UPFC [87]. Furthermore, ST provides lower losses in the line, enhanced the power flow capabilities, and lower cost as compared with that of a PAR [88]. However, since load tap changers inherently possess discrete features, therefore, the ST has output error and slow response. [89], [90].

The ST is developed with the help of nine secondary windings and nine load tap changers, which are in direct contact with the transmission line. The ST deals with the full rated voltage and full fault current. The cost of insulation and machining difficulty will considerably increase when it is used for the EHV and UHV grids [91], [92]. Also, it is challenging to handle system imbalances. Thus, assimilation of ST in an existing transmission system with existing distance relay protections is very challenging.

C. ROTARY POWER FLOW CONTROLLER

The first rotary power flow controller (RPFC) was introduced in 1990s by General Electric Company [93], [94]. The first RPFC was installed by the Chubu Electric Power Company (CEPCO), Japan, at the Sunen substation to control the power flow during normal and blackout conditions [95].

The RPFC is a rotary phase-shifting transformers (RPST) based power flow controller which offers better performance than conventional phase-shifting transformers and power electronic based power flow controllers [79], [96]. The RPFC provides a method for controlling the flow of active and reactive power using series voltage injection to the transmission line which is independent of the line current [97].

The existing research related to RPFC is being carried out based on the steady state model and single-phase equivalent circuit [96], [98]. The other concern is regarding its effect on the power transmission line in terms of safety and stability [99], [100]. Also, the effort has been made for extending the operational range of RPFC using tap-changing transformers [101].

The RPFC consists of series transformer, shunt transformer and two induction machines operating as RPSTs as depicted in Fig. 9 (a). The rotors of the dual RPST are placed on a single-shaft such a way that the rotor angles (α_1 and α_2) are permanently identical and opposite. The shunt transformer has star-delta connection which produces a phase shift of γ-degree (30, 90, etc.) as given in (7) which feeds the shunt-connected rotor windings of the two RPST [102] The series-connected stator windings of the RPSTs is connected through the series transformer in series with the transmission line. The output voltage of the dual RPST is dependent upon the ratios of the transformer winding and the phase angle shift between the stator and the rotor voltage [103]. Hence, the power flow in the transmission line is controlled by adding a controllable series voltage via a conventional series transformer. The phase-shift between the stator and rotor voltages can be regulated by changing the rotor position using the electric drive system or a hydraulic system [104].

The magnitude and phase of the injected series voltage, V_S is calculated by rotor angles of dual RPST (α_1 and α_2).

By neglecting the drop in the voltage across the leakage reactance of the series, shunt, and dual transformers, the magnitude of V_S is given as [102].

$$V_S = T_S V_1 \cos(\delta) \exp^{j(\theta+\gamma)}, \tag{7}$$

where

$$T_S = \frac{T_2 T_R}{T_1}, \tag{8}$$

$$\delta = \frac{\alpha_2 - \alpha_1}{2}, \tag{9}$$

$$\theta = \frac{\alpha_1 + \alpha_2}{2} \tag{10}$$

and T_1 and T_2 represent the turns ratios of the shunt and the series transformers while T_R is the turn ratio of the RPST. The relationship among V_S, V_1 and V_2 using the phasor diagram is depicted in Fig. 9 (b). The V_2 is regulated within the circle as described by the voltage phasor (Fig. 9 (b)). The term $T_S V_1$ represents the radius of the circle which is proportional to the power flow controller equipment rating. However, the RPFC needs separate and special drive systems for the rotation of the rotor shaft [105].

D. CONTROLLABLE NETWORK TRANSFORMERS

The controllable network transformers (CNT) was proposed to control the power transmission between the interconnected power system networks at medium voltages [106], [107]. Moreover, efforts have also been made to escalate the CNT for bulk power transmission levels [108]. The CNT is realized by the load tap changing transformer and a bi-directional direct AC-to-AC converter having fractional rating. The AC-to-AC converter consists of two AC switches S1 and S2, a filter capacitor and an inductor [109].

It is considered that the fixed duty cycles of switches S1 and S2 are D and $(1-D)$. The transformer having the turns ratio of $1:(1+n)$ when the switch S1 is ON and it becomes $1:(1-n)$ when the switch S2 is ON as shown in Fig. 10. The magnitude of output voltage can be controlled ranging from $[1/(1+n)]$ pu to $[1/(1-n)]$ pu with the application of fixed duty cycle D. However, the conventional pulse width modulation (PWM) techniques are unable to regulate the phase angle of the voltage output. Since the energy storage element is absent, therefore, it is unable to supply energy at the instant of zero-crossings of the input voltage. Therefore, the phase angle of output voltage is equal to the input voltage. Hence, the phase angle of output voltage is controlled by the application of dual virtual quadrature sources (DVQS) technique [110], [111]. The voltage output (V_{OUT}) of the CNT is given by [112],

$$V_{OUT} = \left[\frac{D}{1+n} + \frac{1-D}{1-n}\right] V_{IN} \tag{11}$$

where, D, n and V_{IN} are the duty cycle, the tap ratio and input voltage, respectively. According to the energy conservation

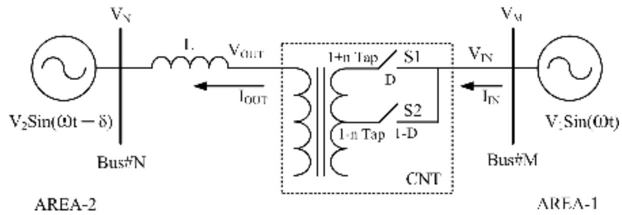

FIGURE 10. Controllable network transformer between two area power networks.

principle, the relationship between the input and output currents can be written as:

$$I_{IN} = \left[\frac{D}{1+n} + \frac{1-D}{1-n}\right] I_{OUT} \tag{12}$$

The Duty cycle D is given by:

$$D = K_0 + K_2 \sin(2\omega t + \phi) \tag{13}$$

The real and reactive power flow through the tie-line with CNT and other related terms are given by:

$$\vec{v}_1 = V_1 \sin(\omega t) \tag{14}$$

$$\vec{v}_2 = V_2 \sin(\omega t - \delta) \tag{15}$$

$$P_{L\_CNT} = \frac{V_1 V_2}{\omega L} [A \sin\delta - B\cos(\delta + \phi)] \tag{16}$$

$$Q_{R\_CNT} = \frac{V_2}{\omega L} [V_2 - AV_1 \cos\delta - BV_1 \sin(\delta + \phi)] \tag{17}$$

$$Q_{S\_CNT} = \frac{V_1}{\omega L}\left[\left(A^2 - \frac{2}{3}B^2\right) V_1 - AV_2 \cos\delta - BV_2 \sin(\delta+\phi)\right] \tag{18}$$

The values of constants A and B is given by

$$A = \frac{1+n-2K_0 n}{1-n^2} \tag{19}$$

$$B = \frac{nK_2}{1-n^2} \tag{20}$$

where V_1 is the sending end and V_2 is the receiving end voltages of a transmission line, respectively; $\omega L = X$ is the reactance of the line and δ is a phase angle between V_1 and V_2; K_0 is the DC component of control reference voltage, and K_2 is the amplitude of second harmonic.

The operating ranges of P and Q are restricted by the duty cycle (D) given in (13) whose value ranging from 0 to 1 and is depends on the parameters of the system. The CNT uses the DVQS technique to regulate the magnitude as well as the phase angle of the line voltage, which provides a dynamic power control. However, DVQS technique exhibit coupling effect among active power and reactive power. Therefore, to implement active power control and reactive power control independently, a decoupled closed-loop controller has been proposed [113]. However, CNT is comprises of power electronic converters which needed a particularly designed filtering system to eliminate third harmonic voltage and current [114].

VI. FACTS DEVICES

Flexible AC Transmission System (FACTS) are an alternating current transmission systems which include a family of power electronic controllers to improve controllability and power transfer capability. Moreover, a FACTS controller is a power electronic system using power semiconductor static devices which provides control of one or more parameters of the AC transmission system [115]. FACTS devices are alternatives for real and reactive power flow control in electrical power transmission systems. The problem of finding optimal location, ratings and type of FACTS device, commonly known as *FACTS allocation problem*, is attracting the attention of researchers [116]–[121]. Depending on the connections topology, the FACTS controllers can be broadly classified as: (i) shunt connected controllers, (ii) series connected controllers, (iii) combined series-series controllers, and (iv) combined shunt-series controllers. In this section, the most versatile FACTS controllers are discussed.

A. UNIFIED POWER FLOW CONTROLLER

The unified power flow controller (UPFC) is the most comprehensive multi-variable voltage source converter (VSC) based FACTS device [122]. The first practical implementation of a 160-MVA UPFC in the world was done by American Electric Power (AEP) at the Inez substation in eastern Kentucky in 1998 [123].

It is able to control, simultaneously or selectively, all three parameters of the power flow equation in the transmission line, viz, voltage magnitude, phase angle as well as line impedance. Alternatively, it can independently control both real and reactive power flow in the transmission line [124]. Typically, a UPFC consists of two VSC connected back to back through a common dc link. One converter is connected in series while the other converter is connected in shunt as shown in Fig. 11(a).

The function of shunt converter is to generate or absorb the real power needed by series converter through the common dc link to support the real power exchange resulting from the series voltage injection. The series converter controls the transmission line real and reactive power flow by injecting a series AC voltage whose magnitude and phase angle are controllable. The transmission line current flows through the series converter which ultimately control or exchange the active and reactive power of the ac power system [125].

The equivalent circuit of UPFC is shown in Fig. 11(b), where the voltage V_1 is the sending end bus voltage that is taken as reference. The injected current of the shunt-converter is $I_2\angle\alpha_2$ and the corresponding output voltage is $V_4\angle\delta_4$. The output voltage of the series-converter is $V_3\angle\delta_3$ and its current is $I_1\angle\alpha_1$, X_1 and X_2 are the leakage reactance of series and shunt transformers, respectively.

To make the analysis simple, the assumption made are: (i) the UPFC regulate the series injected voltage in the transmission line to achieve the power flow control where V_1 is considered constant, (ii) the shunt converter only maintain the DC bus voltage constant, and (iii) all the resistances are neglected. With these assumptions, the sending end real and reactive power of a UPFC is given by [126]:

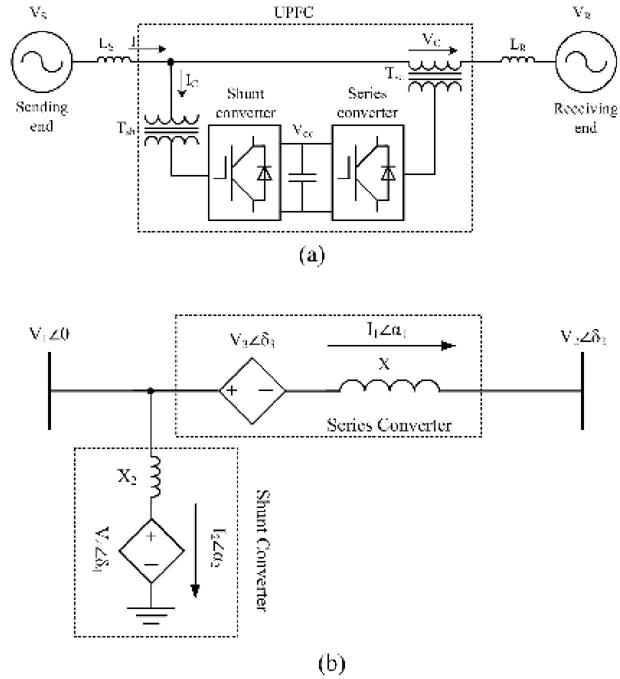

FIGURE 11. The UPFC. (a) Single Line Diagram of UPFC connected to AC system. (b) Single-phase equivalent circuit of UPFC.

$$P_1 = -\frac{V_1V_3}{X_1}\sin\delta_3 - \frac{V_1V_2}{X_1}\sin\delta_2 \quad (21)$$

$$Q_1 = -\frac{V_1V_2}{X_1}\cos\delta_2 + \frac{V_1V_3}{X_1}\cos\delta_3 - \frac{V_1^2}{X_1} \quad (22)$$

Similarly, the real and reactive power at the receiving end of the transmission line is given by:

$$P_2 = \frac{V_1V_2}{X_1}\sin\delta_2 - \frac{V_2V_3}{X_1}\sin(\delta_2-\delta_3) \quad (23)$$

$$Q_2 = \frac{V_2^2}{X_1} - \frac{V_1V_2}{X_1}\cos\delta_2 + \frac{V_2V_3}{X_1}\cos(\delta_2-\delta_3) \quad (24)$$

Although the UPFC has many attractive features in terms of power flow controllability and reliability, but the UPFC is still rarely used for power flow control. This high-voltage, high-power inverters also uses bulky and complicated zigzag transformers of high VA ratings and desired voltage wave forms. The zigzag transformers used are very expensive, lossy, bulky and prone to failure [127]. Further, the shunt and series transformers of the UPFC have to be rated for full voltage and full current, respectively. The UPFC should be properly designed to handle the worst case fault. Moreover, if simultaneous power flow control in more than one line is needed then UPFC seems out of its merits. Hence, multiline voltage-source (VSC) based FACTS controllers, such as an interline power-flow controller (IPFC) is needed [128].

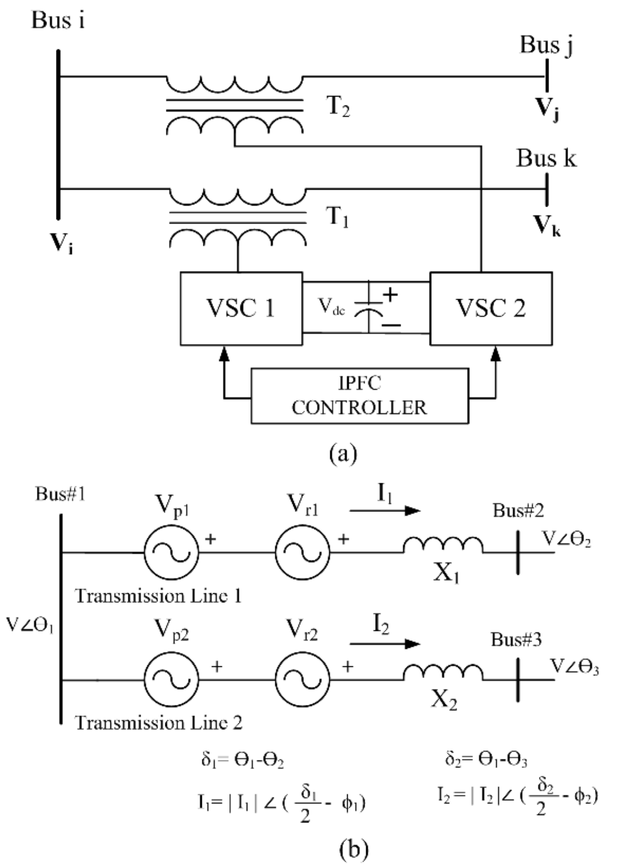

FIGURE 12. **The IPFC. (a) Two-converter based configuration of an IPFC. (b) Equivalent circuit of an IPFC based on two-converter.**

B. INTERLINE POWER FLOW CONTROLLER

The UPFC can be used for effective utilization of individual transmission lines by enabling the independent control of the real and reactive power flow. While the interline power flow controller (IPFC) provides power flow management among a number of transmission lines at a particular substation [129].

An IPFC with two-converters configuration compensating two transmission lines is shown in Figure 12(a). It employs two back-to-back DC-to-AC voltage source converters (VSC). These converters are connected in series with two transmission lines through series transformers and the dc terminals of two converters are connected through a common DC link [130].

Normally, the IPFC employs a number of VSCs linked at a common DC terminal. Each of which can provide series compensation for the selected transmission line. Any converter within the IPFC is able to transfer real power to any other line and thus enables real power transfer among the lines. It also provides independent controllable reactive series compensation of each individual line [131]. The key objective of the IPFC is to optimize both real and reactive power flow among multiple transmission lines, and also transfers power from over-loaded to under-loaded lines. Figure 12(b) shows the equivalent circuit of the IPFC scheme consists of two back-to-back DC-to-DC converters, both compensating a transmission line by series voltage injection [132], [133]. The two synchronous voltage sources, having phasors V_{p1} and V_{p2} in-phase with the transmission lines 1 and 2, represent the two back-to-back DC-to-DC converters. Moreover, the quadrature components of voltage phasors V_{r1} and V_{r2}, also called reactive voltages, are injected into the transmission lines 1 and 2, respectively. The common dc link is represented by a bidirectional link for the real power exchange between the two voltage sources. Transmission line 1, represented by reactance X_1, having sending and receiving end buses with voltage phasors $V\angle\theta_1$ and $V\angle\theta_2$, respectively. Also, transmission line 2, represented by reactance X_2, having a sending and receiving end buses with voltage phasors $V\angle\theta_1$ and $V\angle\theta_3$, respectively. Consider the system with IPFC shown in Fig. 12(b). An expression for the real power and the reactive power injected at the receiving end of the prime line #1 is given by:

$$P_1 = \frac{V^2}{X_1}\sin\delta_1 + \frac{VV_{p1}}{X_1}\sin\left(\frac{\delta_1}{2}-\phi_1\right) + \frac{VV_{r1}}{X_1}\cos\left(\frac{\delta_1}{2}-\phi_1\right) \quad (25)$$

$$Q_1 = \frac{V^2}{X_1}(1-\cos\delta_1) - \frac{VV_{p1}}{X_1}\cos\left(\frac{\delta_1}{2}-\phi_1\right) + \frac{VV_{r1}}{X_1}\sin\left(\frac{\delta_1}{2}-\phi_1\right) \quad (26)$$

However, IPFC has some serious issues such as power flow degradation in the system, the bus voltage variation in presence of the IPFC, and the effect of the transmission angle variation upon the controlled region of the injected series voltages [134]–[136].

VII. ASYNCHRONOUS AC INTERCONNECTIONS TECHNOLOGIES

A. VIRTUAL SYNCHRONOUS MACHINES

The virtual synchronous machines (VSM) is suggested for the integration of distributed generators (DGs) into the utility grid [137]–[141]. It is a power electronic converter which possess the dynamics and the behaviour of the classical synchronous machines. In the control of the converters, mathematical models of the synchronous machine are embedded.

It was first proposal by Beck and Hesse in 2007, and abbreviated as VIrtual Synchronous MAchine (VISMA) [142].

The VSM provides the static and dynamic performance of the traditional electromechanical synchronous machines. It consists of a pulse-generator, a hysteresis controlled three-phase inverter with storage battery and a process computer including voltage and current transducers. A coupling inductance at the AC side is required to operate the inverter in hysteresis control mode [143]. The fundamental structure of the VSM is shown in Fig. 13. A complete operation of VSM involves three sub-processes. It initiate with the real-time measurement of the grid voltage to supply the VSM algorithm with real-time data and on the process computer which performs the mathematical model of a real synchronous machine

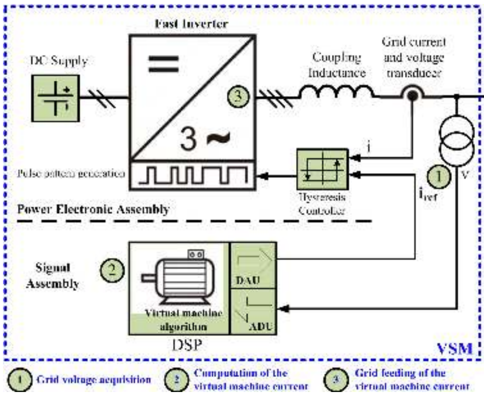

FIGURE 13. Basic structure of the virtual synchronous machines.

under real-time condition. The results are the stator currents of the VSM, which presents process variables. To complete the operation cycle, the calculated stator currents have to take effect at the grid. This is accomplished by a fast hysteresis-controlled inverter which carries the current signals to drive stator currents at the grid immediately.

The governing electromechanical equation of conventional synchronous machine (SM) is also called swing equation which is expressed as [16], [144].

$$J\frac{\mathrm{d}\omega_r}{\mathrm{d}t} + D(\omega_r - \omega_g) = T_m - T_e \tag{27}$$

where J is the angular moment of inertia of the rotor, ω_r and ω_g are the rotor angular frequency and the grid frequency, respectively. D is the damping coefficient of the damper windings, T_m and T_e are the mechanical and electric torque on the shaft, respectively.

The increasing contribution of DGs in the existing power system (grid) results low inertia and low damping which leads to the grid stability issues. A solution in the direction of stability enhancement of this type of grid is to support virtual inertia by employing the virtual synchronous generators (VSGs). This is can be realized by employing the energy storage in addition to a power inverter and a control mechanism [145], [146].

The concept of VSG also called the synchronverter is described in [147]. A self-synchronized synchronverter i.e., without a dedicated synchronization unit for synchronization purposes is also proposed in [148]. A control strategy employed in VSG/VSM called Self-Tuning VSM to improve dynamic frequency control in a diesel-hybrid autonomous power systems is presented in [149], [150].

The transient condition of a micro-grid can be improved by introducing the VSG in the system [151]. Furthermore, a new design of VSG is proposed which improves the voltage sag ride-through capability of the VSG [152], [153]. This is evaluated under different voltage sag conditions [154], [155]. In these proposed works, control of reactive power is added to achieve a constant voltage at VSG terminals [156], [157]. A broad comparison of VSM control algorithms and classification based on model's order is presented in [158], [159].

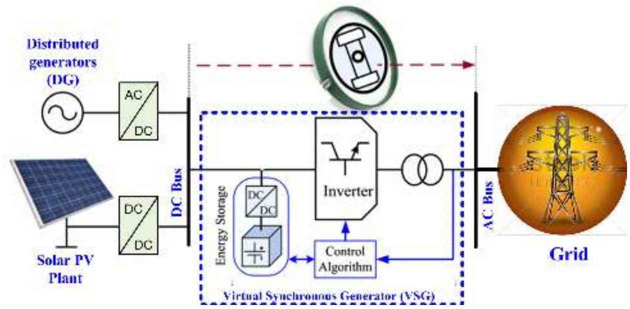

FIGURE 14. Integration of DGs and RESs with the grid through the VSG.

The VSG systems are designed to integrate an energy storage unit to the main AC grid and it has been explained in [160], [161]. Integration of distributed generators (DGs) and renewable energy sources (RES) with the utility grid through the virtual synchronous generator (VSG) is presented in Fig. 14. The VSG is usually deployed between a DC bus and AC bus as depicted in Fig. 14. The VSG exhibit the DC source to the grid as a SG with respect to inertia and damping characteristics. In fact, the imitation of the virtual inertia in the system is facilitated by the real power flow control through the inverter which is inversely proportional to the rotor speed. [9]. Furthermore, the VSG has the ability to supply or absorb power. In normal condition, the nominal state of charge (SOC) of the energy storage in the VSG is operated about 50% of its nominal capacity. The states of operation of VSG can be defined on the basis of SOC condition i.e., according to the specified lower (20%) and upper (80%) limits [162]. The VSG works in active mode, when the SOC is between the lower and upper limits. The VSG works on the virtual load mode when the energy in the system exceeds the limit. The energy storage technology used in VSG, determines these limits. The output active power of a VSG is given by:

$$P_{VSG} = P_0 + K_I\frac{\mathrm{d}\Delta\omega}{\mathrm{d}t} + K_P\Delta\omega \tag{28}$$

and

$$K_I = \frac{2HP_{g0}}{\omega_0} \tag{29}$$

where P_0 is the primary power transferred to the inverter, $\Delta\omega = \omega - \omega_0$ and ω_0 is the grid frequency, K_I is the inertia emulating characteristic, P_{g0} is the nominal apparent power of the generator and H is the amount of inertia. The term $[K_I\mathrm{d}(\Delta\omega)/\mathrm{d}t]$ denotes that power injected or absorbed by the VSG depending upon the positive or the negative sign and $[\mathrm{d}(\Delta\omega)/\mathrm{d}t]$ shows the initial rate of change of frequency.

The K_P imitates the effect of damper windings in a conventional synchronous generator. The value of K_P is taken such that the P_{VSG} becomes equal to the nominal power of the VSG, when the frequency deviation is maximum specified value. The virtual mass counteracts drops in the grid frequency and the virtual damper reduces oscillations in the grid. Therefore, the above properties are uniformly effective to traditional SM. The K_P and K_I are the gains with the

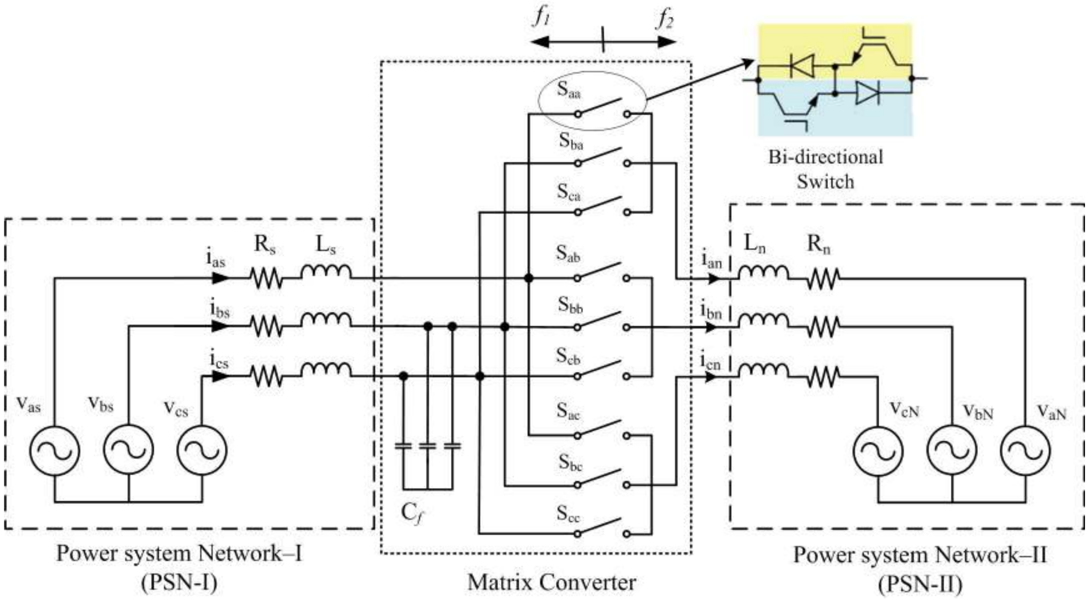

FIGURE 15. Two AC power system networks interconnected by a matrix converter.

negative constant. They should be fixed so that the VSG exchanges its maximum real power. This is achieved when the rate of change of frequency, as well as the specified frequency deviation becomes maximum. The increment in the values of K_P and K_I results more power either generated or absorbed for the same quantity of frequency deviation and the rate of change of frequency [163].

Although, the implementation of VSM causes low-frequency oscillations (LFO) issue in the grid which is generally due to the interaction between the SGs [164].

B. DIRECT AC-TO-AC CONVERTERS

Matrix converter (MC) or AC-to-AC power converters are used in power system networks [165]. A matrix converter is also suggested to interconnect two independent power grids of different voltages and frequencies for the active and reactive power flow control between them [166], [167]. Fig. 15 shows the representation of two AC power system networks interconnected by a matrix converter.

First of all Venturini and Alesina has introduced the idea of direct AC-to-AC power conversion in the year 1980 [168], [169]. They presented the bidirectional power switches of the power converter in a matrix form and they had called it "#1". They have done rigorous mathematical analysis in describing the low-frequency behaviour of the converter through high switching, and introducing the concept of "#1". The concept results in cumbersome equations that makes the performance of the controller sluggish. A simplified work, and that too on an $m \times n$ matrix converter is done in [170]. Fig. 16 shows the 3×3 matrix converter which interfaces a three-phase voltage source with a three-phase load, usually a three-phase AC motor.

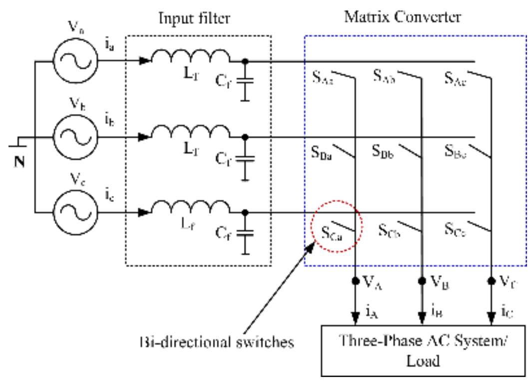

FIGURE 16. Simplified circuit diagram of a 3 × 3 matrix converter.

In general, the MC is fed by a voltage source and, therefore, in any case the input terminals should not be short circuited. Alternatively, typically the load is an inductive in nature and, thus, an output load terminals (phase) must not be opened [171]. The switching function of a single switch is defined as [172]:

$$S_{Kj} = \begin{cases} 1, & \text{if switch } S_{Kj} \text{ is closed} \\ 0, & \text{if switch } S_{Kj} \text{ is open.} \end{cases} \tag{30}$$

where $K = \{A, B, C\}$, and $j = \{a, b, c\}$.

The above constraints can be expressed by

$$S_{Aj} + S_{Bj} + S_{Cj} = 1 \tag{31}$$

The mathematical equation relating the input and the output voltages with reference to Fig. 16 is given by

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix} \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} \tag{32}$$

1) THREE-PHASE AC-TO-AC CONVERTER TOPOLOGIES

The MC is an AC–to–AC power converter based on controllable bi-directional semiconductor switches having no intermediate energy storage element [173]. The physical basis of these converters is the constant instantaneous power delivered by a symmetrical 3-phase voltage–current system. The conventional or direct MC (CMC/DMC) execute the voltage and current conversions in a single stage. The possibility of an indirect conversion by means of an indirect MC (IMC) is also available. Separate stages is necessary for the voltage and current conversions in the IMC. It is analogous to the voltage DC-link back-to-back converter (V-BBC) and the current DC-link back-to-back converter (C-BBC), having no energy storage element in the intermediate stage. Both the MC topologies are implemented by using 18-IGBTs and 18-diodes for fundamental configuration, 18 RB-IGBTs for the CMC and 12 RB-IGBTs and 6 RC-IGBTs for the IMC [174], [175]. Therefore, the intermediate energy storage element is removed at the cost of more semiconductor switches. The forced commutated AC–to–AC converters are classified based on existing literature which is shown in table 1 [176]. Three subgroups are considered as: (i) converters with DC-link energy storage, (ii) MC, and (iii) hybrid MC. A forced commutated AC–to–AC converter is considered as a MC, if it does not need an intermediate energy storage element in the power circuit.

2) CONTROL AND MODULATION TECHNIQUES FOR MC

A brief summary of the control methods and modulation techniques for the MC developed till date is presented in Table 2. The classical and important method is the Venturini method which is also known as the direct transfer function approach. The output voltage obtained is the multiplication of the transfer matrix of the converter and of the input voltage [177]–[180]. An alternative approach proposed by Roy is called the scalar method [181]. In this method, the active and zero states of the switches of the converter is generated by using the instantaneous voltage ratio of a particular input phase voltages. The pulse-width modulation (PWM) techniques is used for the control of MC which was earlier introduced for voltage source inverters. The carrier-based approach of the PWM techniques is the simplest one [182], [183]. The space-vector modulation (SVM) in MCs is the powerful solution which is presently in use [184], [185]. The more recent technique is the predictive control, which is proposed for the current control [186]–[188] and torque control [189]–[191] of AC machines. The major drawback of a matrix converter is it's voltage transfer ratio (VTR). The maximum value of VTR for an $m \times n$ matrix converter is given by [170]:

$$VTR_{max} = \frac{1 + \cos\{\pi/m\}}{2\cos\{\pi/2n\}} \tag{33}$$

where a 3×3 and 3×5 MC give a value of 0.866 and 0.7886, respectively, for multiphase loads [413].

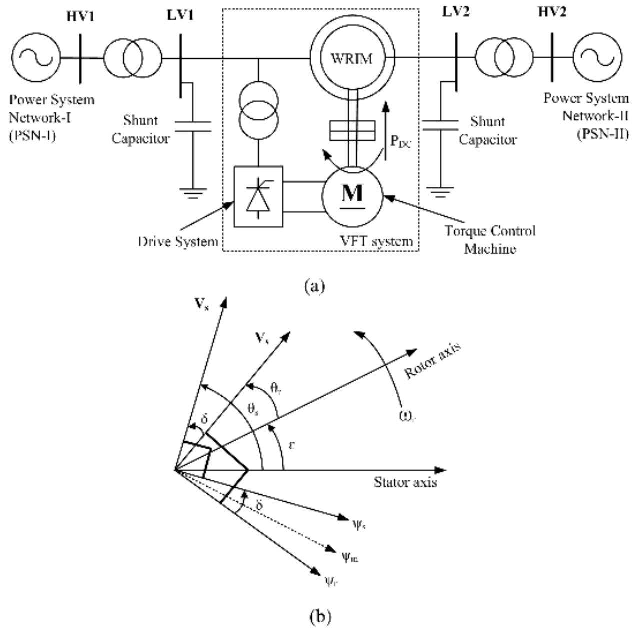

FIGURE 17. **Variable Frequency Transformer (a) Simplified diagram of the variable frequency Transformer (VFT). (b) Phasor diagram of stator and rotor fluxes and voltages in a VFT system.**

C. VARIABLE FREQUENCY TRANSFORMER

The variable frequency transformer (VFT) was developed for the asynchronous interconnections between power grids. First of all it was used for linking the Quebec (Canada) and New York (USA) grids in 2004. It controls the bidirectional power flow between the interconnected power grids [414].

The essential component of the VFT is a doubly fed induction machine (DFIM) operating as rotating transformer having three-phase balanced windings on the stator and the rotor. Basically, VFT is a continuously variable phase-shifting transformer which can operate at an adjustable phase angle. The power system network-I (PSN-I) is connected to the stator windings and the another power system network-II (PSN-II) is connected to the rotor windings of the DFIM as shown in Fig. 17. The real power flow through the VFT is depends on the phase angle and the leakage reactance between the stator and the rotor windings as in any other AC power circuit [415], [416]. A DC motor with its drive system is employed to regulate the rotor speed with respect to the stator. It controls the magnitude and direction of the real power flow through the interconnected system [10].

The magnitude of phase shift depends on the impedance of the rotary transformer and the AC grid. The active power (P_{VFT}) transfer through the VFT with reference to Fig. 17(b), is given by [417],

$$P_{VFT} = \frac{V_s V_r}{X_s} \sin\left[\theta_s - (\theta_r + \epsilon)\right] \tag{34}$$

where V_s and V_r are the rms voltages of stator and rotor, respectively; θ_s and θ_r are the phase angles of stator and rotor voltages, respectively; and X_s is the series equivalent

TABLE 1. Classification of three-phase AC–to–AC converter topologies.

AC–to–AC Converter				
S.No.	Main Classification	Sub-Classification		References
I	Converter with DC-Link storage	Converter with Voltage DC-Link,(V-BBC) ,(VR-VSI)		[192]–[197]
		Converter with Voltage-Current DC-Link, (ZSC, TSC)		[198]–[207]
		Converter with Current DC-Link (C-BBC)		[208]–[215]
II	Hybrid Matrix Converter	Hybrid Direct Matrix Converter (HCMC)		[216]–[220]
		Hybrid Indirect Matrix Converter (HIMC)		[221]–[226]
III	Matrix Converter	Direct Matrix Converter	Conventional Matrix Converter (CMC), (SAX)	[227]–[233]
			Full Bridge Matrix Converter	[234]–[237]
		Indirect Matrix Converter	Converter without DC-Link Capacitor (F3EC)	[238]–[243]
			Indirect Matrix Converter (18-Switch)	[244]–[250]
			Sparse Matrix Converter (SMC, VSMC), (USMC)	[251]–[260]
			Three-Level Matrix Converter	[261]–[269]
		Three-phase Buck Converter (AC-Chopper)		[270]–[278]

TABLE 2. General classification of modulation and control techniques for matrix converters.

Modulation and Methods of Control for Matrix Converter			
S.No.	Classification	Modulation/Control techniques	References
I	Scalar Techniques	Direct Control (Venturini)	[?], [169], [177], [179], [180]
		Scalar (Roy)	[181], [279]–[281]
II	Pulse Width Modulation	Carrier Based	[182], [183], [283]–[292]
		Space Vector Modulation	[172], [184], [185], [293]–[321]
III	Predictive Control	Predictive Current Control	[186]–[188], [249], [322]–[358]
		Predictive Torque Conrol	[188]–[191], [326], [359]–[370]
IV	Direct Torque Control		[371]–[392]
V	Others Techniqes	ANN and Fuzzy logic based Control Techniques	[376], [393]–[412]

inductive reactance offered by the VFT. The ϵ is the time integral of ω_r to be controlled by the application of torque on the rotor shaft by the dc motor.

Power transmission through the VFT is dependent on the torque applied to the rotor. The power flows from the stator connected network to the rotor connected network when the torque is applied in one direction. The direction of power flow will be reversed when the torque is applied in the opposite direction. The magnitude and the direction of power flow is dependent on the magnitude and direction of the torque applied. Irrespective of the power transmission, the rotor of the VFT essentially orients to adopt the phase angle difference created by the interconnected power networks. It will continue to rotate depending upon the difference in the operating frequencies of the power networks.

A variable speed drive system is used to control the DC motor which is employed for the application of torque on the rotor. Two power networks operating at same frequency is interconnected using the VFT system, it will operates at zero speed. Thus, the DC motor and its drive system is designed to provide continuous torque even at zero speed. Although, when there is a frequency deviation due to disturbance in one side of the power system network, the rotor of the VFT will rotate at a speed depending upon the difference in the operating frequencies of the interconnected networks [418].

The performance of VFT under steady-state, dynamic and transient conditions have been evaluated under various simulation environments [419]–[423]. The comparison of various performance parameters with respect to back-to-back HVDC system has also been carried out [424]. The brushless doubly-fed induction machine (BDFIM) with nested cage rotor is proposed as an alternative configuration of the VFT. To avoid space harmonics issue, the double-stator winding with different number of poles having 1:3 ratio is also proposed [425].

In the VFT system, a closed loop power regulator is used to maintain the power transfer equal to an operators' setpoint. The measured power is compared with the setpoint and the power regulator regulates the motor torque as a function of power error. The power regulator is fast to respond to network disturbances which maintains the stable power transfer [426]. The control of decoupled active and reactive power flow through VFT, between two interconnected power system networks has also been presented. Furthermore, the issues of fault spreading and enhancement in the fault ride-through (FRT) capability is also addressed in [417]. The fault ride-through is enhanced by employing a series dynamic braking

TABLE 3. Summary of comparative analysis of power system link and power flow controllers.

Ref. No.	Year	Link/PFC	Contribution	Limitation	Controlled Parameters
[434]	2019	PST	A new technique for the protection of a single core delta-hexagonal PST is presented with less number of CTs per phase.	The relays detect any fault due to the special connection of the transformer. Hence, this technique only employed to delta hexagonal PST.	Power flow control among parallel transmission lines by phase shift between input and output voltages.
[435]	2018	ST	To control the power flow and increase the utilization of the existing transmission lines.	This proposes a IHUPFC which composed of ST and UPFC. The ST has slow response and UPFC causes coplexity and high cost.	Independent control of P and Q using transformer and LTCs.
[436]	2015	RPFC	Steady-state mathematical model, analysis of the control characteristics and relation between rotor angles and injected voltage of RPFC are presented.	Analysis and simulation under steady-state is carried out only. However, transient conditions is not considered.	The rotary phase-shifting transformer (RPST) provide a phase shift which cause modification in power transmission.
[437]	2015	CNTs	A combined CNT-HAF system is proposed to filter out third harmonic voltages and currents in the system.	Since HAF consists of series transformer having full rated current capacity and filter capacitors and inductors. Therefore, it increases the cost and complexity.	Simultaneous control over real and reactive power flow in the transmission network is achieved with minimal harmonics.
[146]	2018	VSM	In this paper, a new inverter controller called eVSM is proposed. This controller improve the transient performance and stability similar to the synchronous generator.	In this paper two assumptions are made such as PLL model is not considered and the phasor domain power equations are considered for instantaneous power. Hence, further research is needed for detailed study.	Improved dynamics and better transient performance are achieved by inertia control.
[438]	2018	MC	The performance of the matrix converter by employing super-junction reverse-blocking insulated gate bipolar transistor (SJ RB-IGBT) switches is investigated in this paper.	The advantages and effectiveness of the SJ RB-IGBT in the MC is verified by simulation and analytical calculation only. Actual practical constraints can only be realized after experimentation.	The low-power loss and superior dynamic performance enables the MC to operate at higher frequency and higher power density.
[439]	2016	VFT	A new VFT configuration is presented to achieve the bidirectional and decoupled active and reactive power flow through VFT.	The proposed VFT configuration consists of shunt and series inverter as well as a DC chopper which inject harmonics in the system.	Independent control over P and Q are achieved.
[440]	2019	LCC-HVDC	A predictive control strategy presented which employed a commutation failure prevention module for mitigating the commutation failures during faults in ac system.	The proposed control strategy employed high level of the DSP controller along with a PMU which increases the overall cost of system.	It temporarily decreases the firing angle of thyristor valves depending on intensity of the fault.
[441]	2019	VSC-HVDC	An adaptive droop control scheme on the basis of both the DC voltage deviation factor and the power sharing factor is proposed.	Effects of varying droop coefficients on the stability of the MTDC system and impacts of line resistances on steady performance of the VSC-MTDC system with the proposed adaptive droop control is not considered.	During large disturbances, DC voltage deviations remain within their limits and power sharing capability of the whole MTDC system remain high.

resistor that limits the fault propagation from the faulty side to the healthy power grid through VFT system.

The application of VFT is also proposed for integration of doubly fed induction machine (DFIM)-based offshore wind farm to utility grid to achieve active power flow control. Moreover, the fluctuations in power generated by wind farm due to irregular wind speed are reduced by PID damping controller [427], [428].

However, a separate DC motor and its drive system is used for controlling the speed, torque, and position of the rotor. This in turn controls the magnitude and direction of power transfer between the networks. Furthermore, the VFT system requires routine shutdown and periodical maintenance for replacement of brushes (carbon) of DC motor [429]. However, under fault condition, VFT requires very high torque to compensate the fault [430]. Hence, a high power DC motor and its drive system become necessary.

D. FLEXIBLE ASYNCHRONOUS AC LINK

A flexible asynchronous AC link (FASAL) system has been recently proposed for an asynchronous interconnection between two electric power system networks. The operating frequencies of these systems may be same or different [431]. The FASAL system is comprises of a doubly fed induction machine (DFIM), voltage regulator and frequency converters. A power systems network-I (PSN-I) is connected to the stator and another power systems network-II (PSN-II) is connected to the rotor. Both the stator and the rotor have

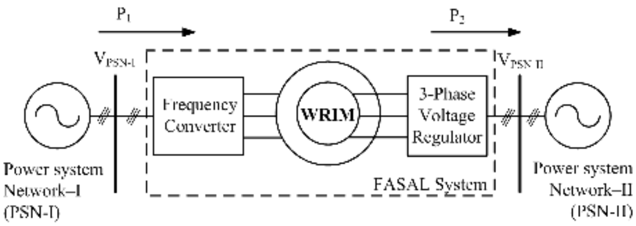

FIGURE 18. A general configuration of the FASAL system.

three-phase symmetrical balanced windings with the equal number of poles.

The control of the voltage and the frequency ultimately controls the magnitude and the direction of power transfer. A general configuration of the FASAL system linking two grids is shown in Fig. 18 [432]. Unlike as reported for VFT in [429], power flows from the higher frequency network side to the lower frequency network side without the use of speed control or position control of rotor.

If the operating frequencies of PSN-I and PSN-II are 60 Hz and 50 Hz, respectively. Then power flows from PSN-I to PSN-II without any application of frequency converter. The amount of power flow is regulated by regulating the voltage by the voltage regulator. If the operating frequencies of PSN-I and PSN-II are same (e.g.,50 Hz), then a frequency converter is used to raise and control the frequency and to control the direction of power flow. The frequency converter is an AC–DC–AC converter which generates voltage at a variable (higher) frequency.

The real and reactive power on both side of the FASAL system is derived on the basis of approximate equivalent circuit of a DFIM [433].

The three–phase real and reactive power at stator side of the FASAL system are given by

$$P_1 = 3\left[R\left(V_1 - \frac{V_2}{s}\cos\delta\right) + X\frac{V_2}{s}\sin\delta\right]\left(\frac{V_1}{Z^2}\right) \quad (35)$$

$$Q_1 = 3\left[X\left(V_1 - \frac{V_2}{s}\cos\delta\right) - R\frac{V_2}{s}\sin\delta\right]\left(\frac{V_1}{Z^2}\right) \quad (36)$$

where $Z = R + jX$ and $Z^2 = R^2 + X^2$

Similarly, the three-phase real and reactive power at rotor side of the FASAL system are given by

$$P_2 = 3\left[XV_1\sin\delta - R\left(\frac{V_2}{s} - V_1\cos\delta\right)\right]\left(-\frac{V_2}{sZ^2}\right) \quad (37)$$

$$Q_2 = 3\left[RV_1\sin\delta + X\left(\frac{V_2}{s} - V_1\cos\delta\right)\right]\left(\frac{V_2}{sZ^2}\right) \quad (38)$$

It is evident from (35) and (37), both P_1 and P_2 depend upon voltage and frequency.

VIII. COMPARATIVE ANALYSIS

A summary of comparative analysis of power system link and power flow controllers based on recent publications is presented in Table 3. In this table contribution, limitation and controlled parameters of recently published papers regarding phase-shifting transformer (PST), sen transformers (ST), rotary power flow controller (RPFC), controllable network transformers (CNTs), virtual synchronous machine (VSM), matrix converter (MC), variable frequency transformer (VFT), line commutated converter based HVDC (LCC-HVDC) and voltage source converter based HVDC (VSC-HVDC) are given in brief.

IX. CONCLUSION

This paper gives a comprehensive review of the interconnections between power system networks. Two methods of interconnections, such as synchronous and asynchronous have been discussed in detail. A broad classification of interconnections of power system networks has been proposed with further subclassification of various power flow controllers which provide a quick review about the topic under consideration. An HVDC asynchronous interconnections and their topologies such as LCC and VSC have been explained too. Some of the existing worldwide projects based on LCC and VSC topologies are also presented with their operating (characteristics) parameters. A comprehensive survey on power flow controllers that are used in interconnected (synchronous) power system networks is discussed in detail with their merits and demerits. These controllers include, PST, PAR, Sen transformer, RPFC, and CNTs. Alternative methods of AC asynchronous interconnections such as application of matrix converter (MC), virtual synchronous machines (VSM), variable frequency transformer (VFT) has also been described with their merits and demerits. Moreover, a recently developed and reported asynchronous AC link called flexible asynchronous AC link (FASAL) system is also presented too. These technologies enable the controllers to transfer power between different grids through interconnections.

REFERENCES

[1] U. Desa, *Multi Dimensional Issues in International Electric Power Grid Interconnections*. New York, NY, USA: United Nations, 2006.
[2] J. Wu, J. Wen, H. Sun, and S. Cheng, “Feasibility study of segmenting large power system interconnections with AC link using energy storage technology,” *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1245–1252, Aug. 2012.
[3] M. Brinkerink, B. Ó. Gallachóir, and P. Deane, “A comprehensive review on the benefits and challenges of global power grids and intercontinental interconnectors,” *Renew. Sustain. Energy Rev.*, vol. 107, pp. 274–287, Jun. 2019.
[4] P. Kundur, *Power System Stability And Control*. New York, NY, USA: McGraw-Hill, 1994.
[5] D. Povh, D. Retzmann, E. Teltsch, U. Kerin, and R. Mihalic, “Advantages of large AC/DC system interconnections,” CIGRE Session, Paris, France, Tech. Rep. B4-304, 2006.
[6] G. Celli, F. Pilo, G. Pisano, R. Cicoria, and A. Iaria, “Meshed vs. Radial MV distribution network in presence of large amount of DG,” in *Proc. IEEE PES Power Syst. Conf. Expo.*, vol. 2, Apr. 2005, pp. 709–714.
[7] D. Das, D. M. Divan, and R. G. Harley, “Power flow control in networks using controllable network transformers,” *IEEE Trans. Power Electron.*, vol. 25, no. 7, pp. 1753–1760, Jul. 2010.
[8] J. Morsali, K. Zare, and M. T. Hagh, “Performance comparison of TCSC with TCPS and SSSC controllers in AGC of realistic interconnected multi-source power system,” *Ain Shams Eng. J.*, vol. 7, no. 1, pp. 143–158, Mar. 2016.

[9] H. Bevrani, T. Ise, and Y. Miura, "Virtual synchronous generators: A survey and new perspectives," *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 244–254, Jan. 2014.
[10] P. Doyon, D. McLaren, M. White, Y. Li, P. Truman, E. Larsen, C. Wegner, E. Pratico, and R. Piwko, "Development of a 100 MW variable frequency transformer," *Canada Power*, pp. 28–30, Sep. 2004.
[11] N. Johansson, L. Angquist, and H.-P. Nee, "Preliminary design of power controller devices using the power-flow control and the ideal phase-shifter methods," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1268–1275, Jul. 2012.
[12] D. Van Hertem, J. Rimez, and R. Belmans, "Power flow controlling devices as a smart and independent grid investment for flexible grid operations: Belgian case study," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1656–1664, Sep. 2013.
[13] I. Ullah, W. Gawlik, and P. Palensky, "Analysis of power network for line reactance variation to improve total transmission capacity," *Energies*, vol. 9, no. 11, p. 936, Nov. 2016.
[14] K. K. Sen, "Practical power flow controller brings benefits of power electronics to the grid," How2Power Today, Tech. Rep., 2015.
[15] N. Friedman. (Sep. 2002). *Distributed Energy Resources Interconnection Systems: Technology Review and Research Needs*. [Online]. Available: http://www.nrel.gov/docs/fy02osti/32459.pdf
[16] D. Chen, Y. Xu, and A. Q. Huang, "Integration of DC microgrids as virtual synchronous machines into the AC grid," *IEEE Trans. Ind. Electron.*, vol. 64, no. 9, pp. 7455–7466, Sep. 2017.
[17] K. R. Padiyar and A. M. Kulkarni, *Dynamics and Control of Electric Transmission and Microgrids*. Hoboken, NJ, USA: Wiley, 2019.
[18] R. M. Hermans, M. Lazar, A. Jokic, and P. P. J. Van Den Bosch, "Almost decentralized model predictive control of power networks," in *Proc. IEEE Medit. Electrotech. Conf. (Melecon)*, Apr. 2010, pp. 1551–1556.
[19] A. Damoiseaux, A. Jokic, M. Lazar, A. Alessio, P. Van den Bosch, I. Hiskens, and A. Bemporad, "Assessment of decentralized model predictive control techniques for power networks," in *Proc. Power Syst. Comput. Conf.*, 2008, pp. 1–9.
[20] A. Alessio and A. Bemporad, "Decentralized model predictive control of constrained linear systems," in *Proc. Eur. Control Conf. (ECC)*, Jul. 2007, pp. 2813–2818.
[21] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, and N. D. Hatziargyriou, "Distributed and decentralized voltage control of smart distribution networks: Models, methods, and future research," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2999–3008, Nov. 2017.
[22] H. Shayeghi, H. Shayanfar, and O. Malik, "Robust decentralized neural networks based LFC in a deregulated power system," *Electric Power Syst. Res.*, vol. 77, nos. 3–4, pp. 241–251, Mar. 2007.
[23] N. Hakimuddin, A. Khosla, and J. K. Garg, "Centralized and decentralized AGC schemes in 2-area interconnected power system considering multi source power plants in each area," *J. King Saud Univ.-Eng. Sciences*, to be published.
[24] A. R. Di Fazio, G. Fusco, and M. Russo, "Decentralized control of distributed generation for voltage profile optimization in smart feeders," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1586–1596, Sep. 2013.
[25] A. Abessi, V. Vahidinasab, and M. S. Ghazizadeh, "Centralized support distributed voltage control by using end-users as reactive power support," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 178–188, Jan. 2016.
[26] M. Nayeripour, H. Fallahzadeh-Abarghouei, E. Waffenschmidt, and S. Hasanvand, "Coordinated online voltage management of distributed generation using network partitioning," *Electr. Power Syst. Res.*, vol. 141, pp. 202–209, Dec. 2016.
[27] M. Seixas, R. Melício, and V. Mendes, "Simulation of rectifier voltage malfunction on OWECS, four-level converter, HVDC light link: Smart grid context tool," *Energy Convers. Manage.*, vol. 97, pp. 140–153, Jun. 2015.
[28] K. Xie, J. Dong, H.-M. Tai, B. Hu, and H. He, "Optimal planning of HVDC-based bundled wind–thermal generation and transmission system," *Energy Convers. Manage.*, vol. 115, pp. 71–79, May 2016.
[29] M. Benasla, T. Allaoui, M. Brahami, M. Denaï, and V. K. Sood, "HVDC links between North Africa and Europe: Impacts and benefits on the dynamic performance of the European system," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3981–3991, Feb. 2018.
[30] K. Padiyar, *HVDC Power Transmission Systems: Technology and System Interactions*. New Delhi, India: New Age International, 1990.
[31] M. Bahrman, "Overview of HVDC transmission," in *Proc. IEEE PES Power Syst. Conf. Expo.*, Oct. 2006, pp. 18–23.
[32] M. Bahrman and B. Johnson, "The ABCs of HVDC transmission technologies," *IEEE Power Energy Mag.*, vol. 5, no. 2, pp. 32–44, Mar. 2007.
[33] S. L. Teichler and I. Levitine, "HVDC transmission: A path to the future?" *Electr. J.*, vol. 23, no. 4, pp. 27–41, May 2010.
[34] M. Saeedifard and R. Iravani, "Dynamic performance of a modular multilevel back-to-back HVDC system," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2903–2912, Oct. 2010.
[35] A. Praça, H. Arakaki, S. Alves, K. Eriksson, J. Graham, and G. Biledt, "Itaipu HVDC transmission system 10 years operational experience," in *Proc. V SEPOPE*, Recife, Brasil, 1996, pp. 1–12.
[36] Q. Y. Yuan and L. Yun, "Xiangjiaba-Shanghai highest power of UHVDC ready for implementation," in *Proc. IEEE/PES Transmiss. Distrib. Conf. Expo.*, Apr. 2008, pp. 1–5.
[37] O. E. Oni, I. E. Davidson, and K. N. I. Mbangula, "A review of LCC-HVDC and VSC-HVDC technologies and applications," in *Proc. IEEE 16th Int. Conf. Environ. Electr. Eng. (EEEIC)*, Jun. 2016, pp. 1–7.
[38] A. M. Vural, "Contribution of high voltage direct current transmission systems to inter-area oscillation damping: A review," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 892–915, May 2016.
[39] S. P. Teeuwsen, "Modeling the trans bay cable project as voltage-sourced converter with modular multilevel converter design," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–8.
[40] J. Egan, P. O'Rourke, R. Sellick, P. Tomlinson, B. Johnson, and S. Svensson, "Overview of the 500MW EirGrid east-west interconnector, considering system design and execution-phase issues," in *Proc. 48th Int. Universities' Power Eng. Conf. (UPEC)*, Sep. 2013, pp. 1–6.
[41] P. L. Francos, S. S. Verdugo, H. F. Alvarez, S. Guyomarch, and J. Loncle, "INELFE—Europe's first integrated onshore HVDC interconnection," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–8.
[42] P. Fairley, "Norway wants to be Europe's battery [News]," *IEEE Spectr.*, vol. 51, no. 11, pp. 13–15, Nov. 2014.
[43] V. K. Sood, "HVDC transmission," in *Power Electronics Handbook*, M. H. Rashid, Ed., 4th ed. Oxford, U.K.: Butterworth-Heinemann, 2018, pp. 847–884.
[44] C. Diemond, J. Bowles, V. Burtnyk, M. Lebow, E. Neudorf, D. Povh, E. Starr, C. Taylor, and R. Walling, "AC-DC economics and alternatives-1987 panel session report," *IEEE Trans. Power Del.*, vol. 5, no. 4, pp. 1956–1979, Oct. 1990.
[45] M. H. Okba, M. H. Saied, M. Z. Mostafa, and T. M. Abdel-Moneim, "High voltage direct current transmission—A review, Part I," in *Proc. IEEE Energytech*, May 2012, pp. 1–7.
[46] H. Wang and M. A. Redfern, "The advantages and disadvantages of using HVDC to interconnect AC networks," in *Proc. IEEE 45th Int. Universities Power Eng. Conf. (UPEC)*, Aug./Sep. 2010, pp. 1–5.
[47] C. Guo and C. Zhao, "Supply of an entirely passive AC network through a double-infeed HVDC system," *IEEE Trans. Power Electron.*, vol. 25, no. 11, pp. 2835–2841, Nov. 2010.
[48] J.-G. Lee, U. A. Khan, H.-Y. Lee, S.-W. Lim, and B.-W. Lee, "Mitigation of commutation failures in LCC–HVDC systems based on superconducting fault current limiters," *Phys. C, Supercond. Appl.*, vol. 530, pp. 160–163, Nov. 2016.
[49] C. Thio, J. Davies, and K. Kent, "Commutation failures in HVDC transmission systems," *IEEE Trans. Power Del.*, vol. 11, no. 2, pp. 946–957, Apr. 1996.
[50] C. Guo, Y. Liu, C. Zhao, X. Wei, and W. Xu, "Power component fault detection method and improved current order limiter control for commutation failure mitigation in HVDC," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1585–1593, Jun. 2015.
[51] Y. Xue, X.-P. Zhang, and C. Yang, "Elimination of commutation failures of LCC HVDC system with controllable capacitors," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 3289–3299, Jul. 2016.
[52] B. Andersen and L. Xu, "Hybrid HVDC system for power transmission to island networks," *IEEE Trans. Power Del.*, vol. 19, no. 4, pp. 1884–1890, Oct. 2004.
[53] C.-K. Kim, "Dynamic coordination strategies between HVDC and STATCOM," in *Proc. Transmiss. Distrib. Conf. Expo., Asia Pacific*, Oct. 2009, pp. 1–9.
[54] C. Guo, Y. Zhang, A. M. Gole, and C. Zhao, "Analysis of dual-infeed HVDC with LCC–HVDC and VSC–HVDC," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1529–1537, Jul. 2012.
[55] C. Zhao, L. Li, G. Li, and C. Guo, "A novel coordinated control strategy for improving the stability of frequency and voltage based on VSC-HVDC," in *Proc. 3rd Int. Conf. Electr. Utility Deregulation Restructuring Power Technol.*, Apr. 2008, pp. 2202–2206.

[56] S. Li, M. Zhou, Z. Liu, J. Zhang, and Y. Li, "A study on VSC–HVDC based black start compared with traditional black start," in *Proc. Int. Conf. Sustain. Power Gener. Supply*, Apr. 2009, pp. 1–6.

[57] A. Kramer and J. Ruff, "Transformers for phase angle regulation considering the selection of on-load tap-changers," *IEEE Trans. Power Del.*, vol. 13, no. 2, pp. 518–525, Apr. 1998.

[58] J. Verboomen, D. Van Hertem, P. Schavemaker, W. Kling, and R. Belmans, "Phase shifting transformers: Principles and applications," in *Proc. Int. Conf. Future Power Syst.*, 2005, p. 6.

[59] J. Verboomen, D. Van Hertem, P. H. Schavemaker, W. L. Kling, and R. Belmans, "Analytical approach to grid operation with phase shifting transformers," *IEEE Trans. Power Syst.*, vol. 23, no. 1, pp. 41–46, Feb. 2008.

[60] J. M. Cano, M. R. R. Mojumdar, J. G. Norniella, and G. A. Orcajo, "Phase shifting transformer model for direct approach power flow studies," *Int. J. Electr. Power Energy Syst.*, vol. 91, pp. 71–79, Oct. 2017.

[61] N. G. Hingorani, L. Gyugyi, and M. El-Hawary, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*, vol. 1. New York, NY, USA: IEEE Press, 2000.

[62] A. S. Siddiqui, S. Khan, S. Ahsan, M. Khan, and Annamalai, "Application of phase shifting transformer in Indian network," in *Proc. Int. Conf. Green Technol. (ICGT)*, Dec. 2012, pp. 186–191.

[63] M. Ramamoorty, L. Toma, M. Eremia, C. Liu, and A. Edris, *Phase Shifting Transformer: Mechanical and Static Devices*, vol. 52. Hoboken, NJ, USA: Wiley, 2016.

[64] J. Faiz and B. Siahkolah, "Differences between conventional and electronic tap-changers and modifications of controller," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1342–1349, Jul. 2006.

[65] C. Masters, "Voltage rise: The big issue when connecting embedded generation to long 11 kV overhead lines," *Power Eng. J.*, vol. 16, no. 1, pp. 5–12, Feb. 2002.

[66] L. Kojovic, "Impact DG on voltage regulation," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, vol. 1, Jun. 2003, pp. 97–102.

[67] D. Gao, Q. Lu, and J. Luo, "A new scheme for on-load tap-changer of transformers," in *Proc. Int. Conf. Power Syst. Technol.*, vol. 2, Jun. 2003, pp. 1016–1020.

[68] G. Ram, V. Prasanth, P. Bauer, and E.-M. Barthlein, "Comparative analysis of on-load tap changing (OLTC) transformer topologies," in *Proc. 16th Int. Power Electron. Motion Control Conf. Expo.*, Sep. 2014, pp. 918–923.

[69] J. H. Harlow, *Electric Power Transformer Engineering*. Boca Raton, FL, USA: CRC Press, 2012.

[70] P. Bauer and S. De Haan, "Solid state tap changers for utility transformers," in *Proc. IEEE Africon. 5th Africon Conf. Afr.*, vol. 2, Jan. 2003, pp. 897–902.

[71] J. Faiz and B. Siahkolah, *Electronic Tap-changer for Distribution Transformers*, vol. 2. Springer, 2011.

[72] G. R. Chandra Mouli, P. Bauer, T. Wijekoon, A. Panosyan, and E.-M. Barthlein, "Design of a power-electronic-assisted OLTC for grid voltage regulation," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1086–1095, Jun. 2015.

[73] M. Iravani and D. Maratukulam, "Review of semiconductor-controlled (static) phase shifters for power systems applications," *IEEE Trans. Power Syst.*, vol. 9, no. 4, pp. 1833–1839, Nov. 1994.

[74] J. Faiz and B. Siahkolah, "New solid-state onload tap-changers topology for distribution transformers," *IEEE Trans. Power Del.*, vol. 18, no. 1, pp. 136–141, Jan. 2003.

[75] A. G. Exposito and D. M. Berjillos, "Solid-state tap changers: New configurations and applications," *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2228–2235, Oct. 2007.

[76] J. Liu, X. Hao, X. Wang, Y. Chen, W. Fang, and S. Niu, "Application of thyristor controlled phase shifting transformer excitation impedance switching control to suppress short-circuit fault current level," *J. Mod. Power Syst. Clean Energy*, vol. 6, no. 4, pp. 821–832, Jul. 2018.

[77] D. J. Rogers and T. C. Green, "A hybrid diverter design for distribution level on-load tap changers," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2010, pp. 1493–1500.

[78] D. J. Rogers and T. C. Green, "An active-shunt diverter for on-load tap changers," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 649–657, Apr. 2013.

[79] E. Larsen, "A classical approach to constructing a power flow controller," in *Proc. IEEE Power Eng. Soc. Summer Meeting. Conf.*, vol. 2, Jan. 2003, pp. 1192–1195.

[80] K. K. Sen and M. L. Sen, "Introducing the family of 'Sen' transformers: A set of power flow controlling transformers," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, vol. 1, Jul. 2002, p. 486.

[81] K. K. Sen and M. L. Sen, "Unique capabilities of Sen transformer: A power flow regulating transformer," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2016, pp. 1–5.

[82] K. K. Sen and M. L. Sen, "Versatile power flow transformers for compensating power flow in a transmission line," U.S. Patent 6 384 581 B1, May 7, 2002.

[83] K. K. Sen and M. L. Sen, "Introducing the family of 'Sen' transformers: A set of power flow controlling transformers," *IEEE Trans. Power Del.*, vol. 18, no. 1, pp. 149–157, Jan. 2003.

[84] M. O. Faruque and V. Dinavahi, "A tap-changing algorithm for the implementation of, 'Sen' transformer," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1750–1757, Jul. 2007.

[85] B. Asghari, O. Faruque, and V. Dinavahi, "Detailed real-time transient modelof the 'Sen' transformer," in *Proc. IEEE Power Energy Soc. Gen. Meeting-Convers. Del. Electr. Energy 21st Century*, Jul. 2008, p. 1.

[86] B. Asghari, M. O. Faruque, and V. Dinavahi, "Detailed real-time transient model of the, 'Sen' transformer," *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1513–1521, Jul. 2008.

[87] K. K. Sen and M. L. Sen, "Comparison of the 'Sen' transformer with the unified power flow controller," *IEEE Trans. Power Del.*, vol. 18, no. 4, pp. 1523–1533, Oct. 2003.

[88] K. K. Sen and M. L. Sen, "Comparison of operational characteristics between a Sen Transformer and a phase angle regulator," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2016, pp. 1–5.

[89] J. Yuan, L. Chen, and B. Chen, "The improved Sen transformer—A new effective approach to power transmission control," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2014, pp. 724–729.

[90] J. Yuan, L. Liu, W. Fei, L. Chen, B. Chen, and B. Chen, "Hybrid electromagnetic unified power flow controller: A novel flexible and effective approach to control power flow," *IEEE Trans. Power Del.*, vol. 33, no. 5, pp. 2061–2069, Oct. 2018.

[91] B. Chen, W. Fei, J. Yuan, and C. Tian, "Research on an improved hybrid unified power flow controller," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2017, pp. 1296–1303.

[92] B. Chen, W. Fei, C. Tian, L. Yang, and J. Gu, "A high-voltage 'Sen' transformer: Configuration, principles, and applications," *Energies*, vol. 11, no. 4, pp. 1–18, 2018.

[93] E. V. Larsen, "Power flow control with rotary transformers," U.S. Patent 5 841 267 A, Nov. 24, 1998.

[94] E. V. Larsen, "Power flow control and power recovery with rotary transformers," U.S. Patent 5 953 225 A, Sep. 14, 1999.

[95] H. Fujita, S. Ihara, E. Larsen, E. Pratico, and W. Price, "Modeling and dynamic performance of a rotary power flow controller," in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf.*, vol. 2, Nov. 2002, pp. 599–604.

[96] H. Fujita, S. Hara, K. Piwko, E. Pratico, and J. Sanchez-Gasca, "Simulator model of rotary power flow controller," in *Proc. Power Eng. Soc. Summer Meeting. Conf.*, vol. 3, Jul. 2001, pp. 1794–1797.

[97] A. O. Ba, T. Peng, and S. Lefebvre, "Rotary power flow controller modeling for dynamic performance evaluation," in *Proc. IEEE Power Energy Soc. Gen. Meeting-Convers. Del. Electr. Energy 21st Century*, Jul. 2008, pp. 1–10.

[98] A. Ba, T. Peng, and S. Lefebvre, "Rotary power-flow controller for dynamic performance evaluation—Part I: RPFC modeling," *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1406–1416, Jul. 2009.

[99] A. Ba, T. Peng, and S. Lefebvre, "Rotary power-flow controller for dynamic performance evaluation—Part II: RPFC application in a transmission corridor," *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1417–1425, Jul. 2009.

[100] M. Tolue Khayami, H. Shayanfar, and A. Kazemi, "Stability analysis of rotary power flow controller," *Int. J. Numer. Model.*, vol. 28, no. 4, pp. 442–455, Jul. 2015.

[101] M. Tolue Khayami and H. Shayanfar, "Extending operational zone of rotary power flow controller by controlling tap-changers of transformers," *Iranian J. Electr. Electron. Eng.*, vol. 10, no. 2, pp. 105–113, 2014.

[102] H. Fujita, S. Ihara, E. Larsen, and W. Price, "Basic characteristics of a rotary power flow controller," in *Proc. IEEE Power Eng. Soc. Winter Meeting Conf.*, vol. 2, Nov. 2002, pp. 1477–1482.

[103] M. H. Abardeh and R. Ghazi, "Rotary power flow controller (RPFC) characteristics analysis," in *Proc. 5th Int. Power Eng. Optim. Conf.*, Jun. 2011, pp. 358–363.

[104] H. Fujita, D. Baker, S. Ihara, E. Larsen, and W. Price, ''Power flow controller using rotary phase-shifting transformers,'' in *Proc. CIGRE Session*, 2000, pp. 37–102.

[105] Z. Chunpeng, J. Qirong, W. Yingdong, H. Chao, C. Yan, and S. Dan, ''A series voltage compensator based on thyristor-controlled transformer,'' in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Nov. 2015, pp. 1–5.

[106] D. Divan and J. Sastry, ''Controllable network transformers,'' in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 2340–2345.

[107] D. Das, D. Divan, and R. G. Harley, ''Implementation of loadflow for networks with controllable network transformers,'' in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2013, pp. 1–6.

[108] A. R. Iyer, P. R. Kandula, R. Moghe, F. C. Lambert, and D. M. Divan, ''Scaling the controllable network transformer (CNT) to utility-level voltages with direct AC/AC power electronic building blocks (PEBBs),'' in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2013, pp. 3049–3056.

[109] F. Kreikebaum, M. Imayavaramban, and D. Divan, ''Active smart wires: An inverter-less static series compensator,'' in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2010, pp. 3626–3630.

[110] D. Divan and J. Sastry, ''Voltage synthesis using dual virtual quadrature sources—A new concept in AC power conversion,'' in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2007, pp. 2678–2684.

[111] D. M. Divan, D. M. Divan, and J. Sastry, ''Voltage synthesis using dual virtual quadrature sources—A new concept in AC power conversion,'' *IEEE Trans. Power Electron.*, vol. 23, no. 6, pp. 3004–3013, Nov. 2008.

[112] D. Das and D. Divan, ''Power flow control in networks using controllable network transformers,'' in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2009, pp. 2224–2231.

[113] H. Chen, A. Iyer, R. Harley, and D. Divan, ''Decoupled closed-loop power flow control for the controllable network transformers (CNT),'' in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2014, pp. 2148–2155.

[114] D. Das, R. Kandula, R. Harley, D. Divan, J. Schatz, and J. Munoz, ''Design and testing of a medium voltage controllable network transformer prototype with an integrated hybrid active filter,'' in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2011, pp. 4035–4042.

[115] N. G. Hingorani and L. Gyugyi, *FACTS Concept and General System Considerations*. Piscataway, NJ, USA: IEEE, 2000.

[116] A. R. Jordehi, ''Particle swarm optimisation (PSO) for allocation of FACTS devices in electric transmission systems: A review,'' *Renew. Sustain. Energy Rev.*, vol. 52, pp. 1260–1267, Dec. 2015.

[117] A. R. Jordehi, ''Optimal allocation of FACTS devices for static security enhancement in power systems via imperialistic competitive algorithm (ICA),'' *Appl. Soft Comput.*, vol. 48, pp. 317–328, Nov. 2016.

[118] A. R. Jordehi, ''Brainstorm optimisation algorithm (BSOA): An efficient algorithm for finding optimal location and setting of FACTS devices in electric power systems,'' *Int. J. Electr. Power Energy Syst.*, vol. 69, pp. 48–57, Jul. 2015.

[119] K. Kavitha and R. Neela, ''Optimal allocation of multi-type FACTS devices and its effect in enhancing system security using BBO, WIPSO & PSO,'' *J. Electr. Syst. Inf. Technol.*, vol. 5, no. 3, pp. 777–793, Dec. 2018.

[120] B. Singh, V. Mukherjee, and P. Tiwari, ''A survey on impact assessment of DG and FACTS controllers in power systems,'' *Renew. Sustain. Energy Rev.*, vol. 42, pp. 846–882, Feb. 2015.

[121] F. H. Gandoman, A. Ahmadi, A. M. Sharaf, P. Siano, J. Pou, B. Hredzak, and V. G. Agelidis, ''Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems,'' *Renew. Sustain. Energy Rev.*, vol. 82, pp. 502–514, Feb. 2018.

[122] L. Gyugyi, C. Schauder, S. Williams, T. Rietman, D. Torgerson, and A. Edris, ''The unified power flow controller: A new approach to power transmission control,'' *IEEE Trans. Power Del.*, vol. 10, no. 2, pp. 1085–1097, Apr. 1995.

[123] L. Liu, P. Zhu, Y. Kang, and J. Chen, ''Power-flow control performance analysis of a unified power-flow controller in a novel control scheme,'' *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1613–1619, Jul. 2007.

[124] A. Rajabi-Ghahnavieh, M. Fotuhi-Firuzabad, M. Shahidehpour, and R. Feuillet, ''UPFC for enhancing power system reliability,'' *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2881–2890, Oct. 2010.

[125] S. Parvathy and K. S. Thampatty, ''Dynamic modeling and control of UPFC for power flow control,'' *Procedia Technol.*, vol. 21, pp. 581–588, 2015.

[126] Y. Jijun, C. Gang, X. Haiqing, L. Qun, L. Jiankun, and L. Peng, ''Principles and functions of UPFC,'' in *Unified Power Flow Controller Technology and Application*, Y. Jijun, C. Gang, X. Haiqing, L. Qun, L. Jiankun, and L. Peng, Eds. New York, NY, USA: Academic, 2017, ch. 2, pp. 19–41.

[127] Y. Liu, S. Yang, X. Wang, D. Gunasekaran, U. Karki, and F. Z. Peng, ''Application of transformer-less UPFC for interconnecting two synchronous AC grids with large phase difference,'' *IEEE Trans. Power Electron.*, vol. 31, no. 9, pp. 6092–6103, Sep. 2016.

[128] M. Khederzadeh and A. Ghorbani, ''Impact of VSC-based multiline FACTS controllers on distance protection of transmission lines,'' *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 32–39, Jan. 2012.

[129] S. Teerathana and A. Yokoyama, ''An optimal power flow control method of power system using interline power flow controller (IPFC),'' in *Proc. IEEE Region 10 Conf. TENCON*, May 2005, pp. 343–346.

[130] K. R. Padiyar and N. Prabhu, ''Analysis of SSR with three-level twelve-pulse VSC-based interline power-flow controller,'' *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1688–1695, Jul. 2007.

[131] N. M. Santos, O. Dias, and V. F. Pires, ''Use of an interline power flow controller model for power flow analysis,'' *Energy Procedia*, vol. 14, pp. 2096–2101, 2012.

[132] K. R. Padiyar, *FACTS Controllers in Power Transmission and Distribution*. New Delhi, India: New Age International, 2007.

[133] R. L. Vasquez-Arnez and F. A. Moreira, ''The interline power flow controller: Further aspects related to its operation and main limitations,'' in *Proc. IEEE/PES Transmiss. Distrib. Conf. Expo.*, Apr. 2008, pp. 1–6.

[134] R. Vasquez-Arnez and L. Zanetta, ''A novel approach for modeling the steady-state VSC-based multiline FACTS controllers and their operational constraints,'' *IEEE Trans. Power Del.*, vol. 23, no. 1, pp. 457–464, Jan. 2008.

[135] R. L. Vasquez-Arnez and F. A. Moreira, ''Main advantages and limitations of the interline power flow controller: A steady-state analysis,'' in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jul. 2008, pp. 1–6.

[136] M. Ebeed, S. Kamel, and F. Jurado, ''Determination of IPFC operating constraints in power flow analysis,'' *Int. J. Electr. Power Energy Syst.*, vol. 81, pp. 299–307, Oct. 2016.

[137] Q.-C. Zhong, ''Virtual synchronous machines: A unified interface for grid integration,'' *IEEE Power Electron. Mag.*, vol. 3, no. 4, pp. 18–27, Dec. 2016.

[138] J. Liu, Y. Miura, and T. Ise, ''Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators,'' *IEEE Trans. Power Electron.*, vol. 31, no. 5, pp. 3600–3611, May 2016.

[139] S. D'Arco, J. A. Suul, and O. B. Fosso, ''A virtual synchronous machine implementation for distributed control of power converters in SmartGrids,'' *Electr. Power Syst. Res.*, vol. 122, pp. 180–197, May 2015.

[140] Z. Ma, Q.-C. Zhong, and J. D. Yan, ''Synchronverter-based control strategies for three-phase PWM rectifiers,'' in *Proc. 7th IEEE Conf. Ind. Electron. Appl. (ICIEA)*, Jul. 2012, pp. 225–230.

[141] M. Ebrahimi, S. A. Khajehoddin, and M. Karimi-Ghartemani, ''An improved damping method for virtual synchronous machines,'' *IEEE Trans. Sustain. Energy*, vol. 10, no. 3, pp. 1491–1500, Jul. 2019.

[142] H.-P. Beck and R. Hesse, ''Virtual synchronous machine,'' in *Proc. 9th Int. Conf. Electr. Power Qual. Utilisation*, Oct. 2007, pp. 1–6.

[143] Y. Chen, R. Hesse, D. Turschner, and H.-P. Beck, ''Improving the grid power quality using virtual synchronous machines,'' in *Proc. Int. Conf. Power Eng., Energy Electr. Drives*, May 2011, pp. 1–6.

[144] S. A. Khajehoddin, M. Karimi-Ghartemani, and M. Ebrahimi, ''Grid-supporting inverters with improved dynamics,'' *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 3655–3667, May 2019.

[145] J. Driesen and K. Visscher, ''Virtual synchronous generators,'' in *Proc. IEEE Power Energy Soc. Gen. Meeting-Convers. Del. Electr. Energy 21st Century*, Jul. 2008, pp. 1–3.

[146] M. Van Wesenbeeck, S. De Haan, P. Varela, and K. Visscher, ''Grid tied converter with virtual kinetic storage,'' in *Proc. IEEE Bucharest PowerTech*, Jun. 2009, pp. 1–7.

[147] Q.-C. Zhong and G. Weiss, ''Synchronverters: Inverters that mimic synchronous generators,'' *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.

[148] Q.-C. Zhong, P.-L. Nguyen, Z. Ma, and W. Sheng, ''Self-synchronized synchronverters: Inverters without a dedicated synchronization unit,'' *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 617–630, Feb. 2014.

[149] M. Torres and L. A. C. Lopes, ''Virtual synchronous generator: A control strategy to improve dynamic frequency control in autonomous power systems,'' *Energy Power Eng.*, vol. 5, no. 2, pp. 32–38, 2013.

[150] L. M. A. Torres, L. A. C. Lopes, T. L. A. Moran, and C. J. R. Espinoza, ''Self-tuning virtual synchronous machine: A control strategy for energy storage systems to support dynamic frequency control,'' *IEEE Trans. Energy Convers.*, vol. 29, no. 4, pp. 833–840, Dec. 2014.

[151] N. Soni, S. Doolla, and M. C. Chandorkar, ''Improvement of transient response in microgrids using virtual inertia,'' *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1830–1838, Jul. 2013.

[152] K. Sakimoto, Y. Miura, and T. Ise, ''Stabilization of a power system with a distributed generator by a virtual synchronous generator function,'' in *Proc. Int. Conf. Power Electron. ECCE Asia*, May 2011, pp. 1498–1505.

[153] J. Alipoor, Y. Miura, and T. Ise, ''Power system stabilization using virtual synchronous generator with alternating moment of inertia,'' *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 2, pp. 451–458, Jun. 2015.

[154] J. Alipoor, Y. Miura, and T. Ise, ''Evaluation of virtual synchronous generator (VSG) operation under different voltage sag conditions,'' in *Proc. IEE Jpn. Joint Tech. Meeting Power Eng. Power Syst. Eng.*, Tokyo, Japan, vol. 52, 2012, pp. 41–46.

[155] J. Alipoor, Y. Miura, and T. Ise, ''Voltage sag ride-through performance of virtual synchronous generator,'' in *Proc. Int. Power Electron. Conf.*, May 2014, pp. 3298–3305.

[156] T. Shintai, Y. Miura, and T. Ise, ''Reactive power control for load sharing with virtual synchronous generator control,'' in *Proc. 7th Int. Power Electron. Motion Control Conf.*, vol. 2, Jun. 2012, pp. 846–853.

[157] S. M. Amrr, M. S. Alam, M. S. J. Asghar, and F. Ahmad, ''Low cost residential microgrid system based home to grid (H2G) back up power management,'' *Sustain. Cities Soc.*, vol. 36, pp. 204–214, Jan. 2018.

[158] S. D'Arco and J. A. Suul, ''Virtual synchronous machines—Classification of implementations and analysis of equivalence to droop controllers for microgrids,'' in *Proc. IEEE Grenoble Conf.*, Jun. 2013, pp. 1–7.

[159] H. Alrajhi Alsiraji and R. El-Shatshat, ''Comprehensive assessment of virtual synchronous machine based voltage source converter controllers,'' *IET Gener., Transmiss. Distrib.*, vol. 11, no. 7, pp. 1762–1769, May 2017.

[160] M. Torres and L. A. C. Lopes, ''Virtual synchronous generator control in autonomous wind-diesel power systems,'' in *Proc. IEEE Electr. Power Energy Conf. (EPEC)*, Oct. 2009, pp. 1–6.

[161] V. Karapanos, S. De Haan, and K. Zwetsloot, ''Real time simulation of a power system with VSG hardware in the loop,'' in *Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2011, pp. 3748–3754.

[162] M. Albu, J. Diaz, V. Thong, R. Neurohr, D. Federenciuc, M. Popa, and M. Calin, ''Measurement and remote monitoring for virtual synchronous generator design,'' in *Proc. IEEE Int. Workshop Appl. Meas. Power Syst.*, Sep. 2010, pp. 7–11.

[163] V. Karapanos, S. de Haan, and K. Zwetsloot, ''Testing a virtual synchronous generator in a real time simulated power system,'' in *Proc. Int. Conf. Power Syst. Transients (IPST)*, 2011, pp. 1–7.

[164] L. Huang, H. Xin, and Z. Wang, ''Damping low-frequency oscillations through vsc-hvdc stations operated as virtual synchronous machines,'' *IEEE Trans. Power Electron.*, vol. 34, no. 6, pp. 5803–5818, Jun. 2019.

[165] P. Szczesniak and Z. Fedyczak, ''Application of the matrix converter to power flow control,'' *Arch. Electr. Eng.*, vol. 63, no. 3, pp. 409–422, Sep. 2014.

[166] H. Nikkhajoei, A. Tabesh, and R. Iravani, ''Dynamic model of a matrix converter for controller design and system studies,'' *IEEE Trans. Power Del.*, vol. 21, no. 2, pp. 744–754, Apr. 2006.

[167] Y. Liu, Y. Liu, B. Ge, and H. Abu-Rub, ''Interactive grid interfacing system by matrix-converter based solid state transformer with model predictive control,'' *IEEE Trans. Ind. Inf.*, to be published.

[168] M. Venturini, ''A new sine wave in sine wave out, conversion technique which eliminates reactive elements,'' in *Proc. POWERCON*, vol. 7, 1980, pp. E3-1–E3-15.

[169] M. Venturini and A. Alesina, ''The generalised transformer: A new bidirectional, sinusoidal waveform frequency converter with continuously adjustable input power factor,'' in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 1980, pp. 242–252.

[170] M. Ali, A. Iqbal, M. R. Khan, M. Ayyub, and M. A. Anees, ''Generalized theory and analysis of scalar modulation techniques for a $m \times n$ matrix converter,'' *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4864–4877, Jun. 2017.

[171] P. Wheeler, J. Rodriguez, J. Clare, L. Empringham, and A. Weinstein, ''Matrix converters: A technology review,'' *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 276–288, Apr. 2002.

[172] L. Huber and D. Borojevic, ''Space vector modulated three-phase to three-phase matrix converter with input power factor correction,'' *IEEE Trans. Ind. Appl.*, vol. 31, no. 6, pp. 1234–1246, Nov. 1995.

[173] P. Szczesniak, J. Kaniewski, and M. Jarnut, ''AC–AC power electronic converters without DC energy storage: A review,'' *Energy Convers. Manage.*, vol. 92, pp. 483–497, Mar. 2015.

[174] S. Bernet, T. Matsuo, and T. Lipo, ''A matrix converter using reverse blocking NPT-IGBTs and optimized pulse patterns,'' in *Proc. PESC Record. 27th Annu. IEEE Power Electron. Spec. Conf.*, vol. 1, Dec. 2002, pp. 107–113.

[175] E. Motto, J. Donlon, M. Tabata, H. Takahashi, Y. Yu, and G. Majumdar, ''Application characteristics of an experimental RB-IGBT (reverse blocking IGBT) module,'' in *Proc. Conf. Rec. IEEE Ind. Appl. Conf., 39th IAS Annu. Meeting.*, vol. 3, Nov. 2004, pp. 1540–1544.

[176] J. W. Kolar, T. Friedli, J. Rodriguez, and P. W. Wheeler, ''Review of three-phase PWM AC–AC converter topologies,'' *IEEE Trans. Ind. Electron.*, vol. 58, no. 11, pp. 4988–5006, Nov. 2011.

[177] L. Zhang, C. Watthanasarn, and W. Shepherd, ''Control of AC-AC matrix converters for unbalanced and/or distorted supply voltage,'' in *Proc. IEEE 32nd Annu. Power Electron. Spec. Conf.*, vol. 2, Nov. 2002, pp. 1108–1113.

[178] J. Rodriguez, E. Silva, F. Blaabjerg, P. Wheeler, J. Clare, and J. Pontt, ''Matrix converter controlled with the direct transfer function approach: Analysis, modelling and simulation,'' *Int. J. Electron.*, vol. 92, no. 2, pp. 63–85, 2005.

[179] J. Rzasa, ''Capacitor clamped multilevel matrix converter controlled with venturini method,'' in *Proc. 13th Int. Power Electron. Motion Control Conf.*, Sep. 2008, pp. 357–364.

[180] S. L. Arevalo, P. Zanchetta, P. W. Wheeler, A. Trentin, and L. Empringham, ''Control and implementation of a matrix-converter-based AC ground power-supply unit for aircraft servicing,'' *IEEE Trans. Ind. Electron.*, vol. 57, no. 6, pp. 2076–2084, Jun. 2010.

[181] G. Roy and G.-E. April, ''Cycloconverter operation under a new scalar control algorithm,'' in *Proc. Annu. IEEE Power Electron. Spec. Conf.*, vol. 1, Jan. 2003, pp. 368–375.

[182] B. Wang and G. Venkataramanan, ''A carrier based PWM algorithm for indirect matrix converters,'' in *Proc. 37th IEEE Power Electron. Spec. Conf.*, Jun. 2006, pp. 1–8.

[183] P. Potamianos, E. Mitronikas, and A. Safacas, ''A modified carrier-based modulation method for three-phase matrix converters,'' in *Proc. IEEE 13th Eur. Conf. Power Electron. Appl.*, Sep. 2009, pp. 1–9.

[184] S. G. Kumar, S. S. Sankar, S. K. Kumar, and G. Uma, ''Implementation of space vector modulated 3ϕ to $3\ \phi$ matrix converter fed induction motor,'' in *Proc. 7th Int. Conf. Power Electron. Drive Syst.*, Nov. 2007, pp. 1483–1486.

[185] H. She, H. Lin, X. Wang, and S. Xiong, ''Space vector modulated matrix converter under abnormal input voltage conditions,'' in *Proc. IEEE 6th Int. Power Electron. Motion Control Conf.*, May 2009, pp. 1723–1727.

[186] M. Vijayagopal, C. Silva, L. Empringham, and L. De Lillo, ''Direct predictive current-error vector control for a direct matrix converter,'' *IEEE Trans. Power Electron.*, vol. 34, no. 2, pp. 1925–1935, Feb. 2019.

[187] T. N. Mir, B. Singh, and A. H. Bhat, ''Low speed sensorless model predictive current control of a three phase induction motor from a single phase supply,'' in *Proc. IEEMA Engineer Infinite Conf. (eTechNxT)*, Mar. 2018, pp. 1–6.

[188] O. Gulbudak and M. Gokdag, ''Improving supply current quality of dual-output four-leg indirect matrix converter using model predictive control,'' in *Proc. IEEE 12th Int. Conf. Compat., Power Electron. Power Eng. (CPE-POWERENG)*, Apr. 2018, pp. 1–6.

[189] Y. Jang, Y. Bak, and K.-B. Lee, ''Indirect matrix converter for permanent-magnet-synchronous-motor drives by improved torque predictive control,'' in *Proc. Int. Power Electron. Conf. (IPEC-Niigata-ECCE Asia)*, May 2018, pp. 1736–1740.

[190] Y. Mei, L. Wang, W. Huang, and S. Niu, ''An improved zero current commutation model predictive torque control method for the induction motor drives fed by indirect matrix converter,'' in *Proc. 21st Int. Conf. Electr. Mach. Syst. (ICEMS)*, Oct. 2018, pp. 1476–1480.

[191] M. Siami, M. Amiri, H. K. Savadkoohi, R. Rezavandi, and S. Valipour, ''Simplified predictive torque control for a PMSM drive fed by a matrix converter with imposed input current,'' *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 6, no. 4, pp. 1641–1649, Dec. 2018.

[192] L. Malesani, L. Rossetto, P. Tenti, and P. Tomasin, ''AC/DC/AC PWM converter with minimum energy storage in the DC link,'' in *Proc. 8th Annu. Appl. Power Electron. Conf. Expo.*, Dec. 2002, pp. 306–311.

[193] H. Xie, L. Angquist, and H.-P. Nee, "Design and analysis of a controller for a converter interface interconnecting an energy storage with the Dc link of a VSC," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 1007–1015, May 2010.

[194] H. Xie, L. Angquist, and H.-P. Nee, "Design study of a converter interface interconnecting an energy storage with the dc-link of a VSC," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT Eur.)*, Oct. 2010, pp. 1–9.

[195] T. Friedli and J. W. Kolar, "Comprehensive comparison of three-phase AC-AC matrix converter and voltage DC-link back-to-back converter systems," in *Proc. IEEE Int. Power Electron. Conf.*, Jun. 2010, pp. 2789–2798.

[196] T. Friedli, J. W. Kolar, J. Rodriguez, and P. W. Wheeler, "Comparative evaluation of three-phase AC–AC matrix converter and voltage DC-link back-to-back converter systems," *IEEE Trans. Ind. Electron.*, vol. 59, no. 12, pp. 4487–4510, Dec. 2012.

[197] P. Rumniak, M. Michalczuk, A. Kaszewski, A. Galecki, and L. Grzesiak, "DC-link voltage control strategy for an NPC voltage source converters in an effective energy storage system," in *Proc. 19th Eur. Conf. Power Electron. Appl. (EPE ECCE Eur.)*, Sep. 2017, p. 1.

[198] F. Z. Peng, "Z-source inverter," *IEEE Trans. Ind. Appl.*, vol. 39, no. 2, pp. 504–510, Mar./Apr. 2003.

[199] F. Peng, X. Yuan, X. Fang, and Z. Qian, "Z-source inverter for adjustable speed drives," *IEEE Power Electron. Lett.*, vol. 1, no. 2, pp. 33–35, Jun. 2003.

[200] F. Z. Peng, A. Joseph, J. Wang, M. Shen, L. Chen, Z. Pan, E. Ortiz-Rivera, and Y. Huang, "Z-source inverter for motor drives," *IEEE Trans. Power Electron.*, vol. 20, no. 4, pp. 857–863, Jul. 2005.

[201] X. Hou, F. Alskran, and M. G. Simoes, "A DSP based modeling and digital control of single phase quasi-Z-source inverter," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2018, pp. 2250–2257.

[202] K. Choobdari Omran and A. Mosallanejad, "SMES/battery hybrid energy storage system based on bidirectional Z-source inverter for electric vehicles," *IET Electr. Syst. Transp.*, vol. 8, no. 4, pp. 215–220, Dec. 2018.

[203] M. Yaghoubi, J. S. Moghani, N. Noroozi, and M. R. Zolghadri, "IGBT open-circuit fault diagnosis in a quasi-z-source inverter," *IEEE Trans. Ind. Electron.*, vol. 66, no. 4, pp. 2847–2856, Apr. 2019.

[204] R. Strzelecki, M. Adamowicz, N. Strzelecka, and W. Bury, "New type t-source inverter," in *Proc. Compatability Power Electron.*, May 2009, pp. 191–195.

[205] P. Sivaraman and R. Desanayagi, "Performance analysis of PV fed single phase T-source inverter," in *Proc. Int. Conf. Power, Energy Control (ICPEC)*, Feb. 2013, pp. 266–271.

[206] Q.-V. Tran, K.-S. Low, A.-V. Ho, and T.-W. Chun, "A new current-type magnetically coupled T-source inverter," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Feb. 2014, pp. 318–323.

[207] T. Tharani, J. X. A. Ancy, and G. Bakiyalakshmi, "SAG mitigation of VSD using t-source inverter," in *Proc. 3rd Int. Conf. Sci. Technol. Eng. Manage. (ICONSTEM)*, Mar. 2017, pp. 645–648.

[208] K. Kuusela, M. Salo, and H. Tuusa, "A current source PWM-converter fed permanent magnet synchronous motor drive with adjustable dc-link current," in *Proc. NORPIE*, 2000, pp. 54–58.

[209] F. W. Fuchs and A. Kloenne, "DC link and dynamic performance features of PWM IGBT current source converter induction machine drives with respect to industrial requirements," in *Proc. IPEMC*, vol. 3, 2004, pp. 1393–1398.

[210] M. Bierhoff and F. Fuchs, "Semiconductor losses in voltage source and current source IGBT converters based on analytical derivation," in *Proc. IEEE 35th Annu. Power Electron. Spec. Conf.*, vol. 4, Jan. 2005, pp. 2836–2842.

[211] Z. Bai and Z. Zhang, "Digital control technique for multi-module current source converter," in *Proc. IEEE Int. Conf. Ind. Technol.*, Apr. 2008, pp. 1–5.

[212] M. F. Naguib and L. A. C. Lopes, "A hybrid bi-directional current source converter with two force-commutated switches and controlled with space vector modulation," in *Proc. Can. Conf. Electr. Comput. Eng.*, May 2008, pp. 173–178.

[213] R. E. Alzate and J. Posada, "Design and implementation of proportional-resonant controller for 3-phase current source inverter in Dspace DS1104," in *Proc. IEEE Workshop Power Electron. Power Qual. Appl. (PEPQA)*, May 2017, pp. 1–6.

[214] S.-S. Choi, C.-W. Lee, I.-D. Kim, J. H. Jung, and D. H. Seo, "New induction heating power supply for forging applications using IGBT current-source PWM rectifier and inverter," in *Proc. 21st Int. Conf. Electr. Mach. Syst. (ICEMS)*, Oct. 2018, pp. 709–713.

[215] X. Guo, Y. Yang, and X. Wang, "Optimal space vector modulation of current-source converter for DC-link current ripple reduction," *IEEE Trans. Ind. Electron.*, vol. 66, no. 3, pp. 1671–1680, Mar. 2019.

[216] T. Wijekoon, C. Klumpner, and P. Wheeler, "Implementation of a hybrid AC/AC direct power converter with unity voltage transfer ratio," in *Proc. 21st Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Apr. 2006, pp. 1–7.

[217] T. Wijekoon, C. Klumpner, P. Zanchetta, and P. Wheeler, "Implementation of a Hybrid AC–AC direct power converter with unity voltage transfer," *IEEE Trans. Power Electron.*, vol. 23, no. 4, pp. 1918–1926, Jul. 2008.

[218] C. Klumpner and C. Pitic, "Hybrid matrix converter topologies: An exploration of benefits," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 2–8.

[219] A. Janabi and B. Wang, "Hybrid matrix converter based on instantaneous reactive power theory," in *Proc. 41st Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2015, pp. 3910–3915.

[220] J. Kaniewski, "Hybrid distribution transformer based on a bipolar direct AC/AC converter," *IET Electr. Power Appl.*, vol. 12, no. 7, pp. 1034–1039, Aug. 2018.

[221] C. Klumpner, "Hybrid indirect matrix converter immune to unbalanced voltage supply, with reduced switching losses and improved voltage transfer ratio," in *Proc. 21st Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Apr. 2006, pp. 1–7.

[222] K. Kato and J.-I. Itoh, "Control strategy for a buck-boost type direct interface converter using an indirect matrix converter with an active snubber," in *Proc. 25th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Feb. 2010, pp. 1684–1691.

[223] C. Raja, A. Prabha, and S. Sivaranjani, "Reactive power minimization and unity voltage transfer in a distorted AC supply by using hybrid indirect matrix converter," in *Proc. Int. Conf. Inf. Commun. Embedded Syst.*, Feb. 2014, pp. 1–5.

[224] M. Hamouda, H. F. Blanchette, and K. Al-Haddad, "A hybrid modulation scheme for dual-output five-leg indirect matrix converter," *IEEE Trans. Ind. Electron.*, vol. 63, no. 12, pp. 7299–7309, Dec. 2016.

[225] A. Ammar, H. Y. Kanaan, N. Moubayed, M. Hamouda, and K. Al-Haddad, "A novel hybrid modulation algorithm for the indirect matrix converter topology," in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2017, pp. 6363–6368.

[226] A. Ammar, H. Y. Kanaan, N. Moubayed, M. Hamouda, and K. Al-Haddad, "A simple hybrid PWM algorithm for a five-phase indirect matrix converter topology," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Feb. 2018, pp. 1909–1914.

[227] L. Wei, T. Lipo, and H. Chan, "Robust voltage commutation of the conventional matrix converter," in *Proc. IEEE 34th Annu. Conf. Power Electron. Spec. (PESC)*, vol. 2, Oct. 2003, pp. 717–722.

[228] M. Ziegler, D. Domes, W. Hofmann, and S. El-Barbari, "A new rectifier based topology for electrical drives: S-A-X -converter," in *Proc. IEEE 35th Annu. Power Electron. Spec. Conf.*, vol. 4, Jan. 2005, pp. 2924–2928.

[229] F. Schafmeister, C. Rytz, and J. Kolar, "Analytical calculation of the conduction and switching losses of the conventional matrix converter and the (very) sparse matrix converter," in *Proc. 20th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, vol. 2, Jun. 2005, pp. 875–881.

[230] R. Rong, P. C. Loh, P. Wang, and F. Blaabjerg, "A three-level 4×3 conventional matrix converter," in *Proc. 7th Int. Conf. Power Electron. Drive Syst.*, Nov. 2007, pp. 315–319.

[231] L. Wei, R. A. Lukaszewski, and T. A. Lipo, "Analysis of power cycling capability of IGBT modules in a conventional matrix converter," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Oct. 2008, pp. 1–8.

[232] M. Chai, R. Dutta, and J. E. Fletcher, "Space vector PWM for five-to-three phase conventional matrix converter with d2–q2 vector elimination," in *Proc. IEEE ECCE Asia Downunder*, Jun. 2013, pp. 1328–1333.

[233] G. Zhang, J. Yang, Y. Sun, M. Su, Q. Zhu, and F. Blaabjerg, "A predictive-control-based over-modulation method for conventional matrix converters," *IEEE Trans. Power Electron.*, vol. 33, no. 4, pp. 3631–3643, Apr. 2018.

[234] M. Braun and K. Hasse, "A direct frequency changer with control of input reactive power," *IFAC Proc.*, vol. 16, no. 16, pp. 187–194, 1983.

[235] K. K. Mohapatra and N. Mohan, "Open-end winding induction motor driven with matrix converter for common-mode elimination," in *Proc. Int. Conf. Power Electron., Drives Energy Syst.*, Dec. 2006, pp. 1–6.

[236] S. Tewari, R. K. Gupta, A. Somani, and N. Mohan, "A new sinusoidal input-output three-phase full-bridge direct power converter," in *Proc. 39th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2013, pp. 4824–4830.

[237] Y. Li and H. Wei, "Research on controlling strategy of dual bridge matrix converter-direct torque control of induction motor," *Energy Procedia*, vol. 16, pp. 1650–1658, 2012.

[238] T. Habetler and D. Divan, "Rectifier/invertor reactive component minimization," *IEEE Trans. Ind. Appl.*, vol. 25, no. 2, pp. 307–316, Mar./Apr. 1989.

[239] S. Kim, S.-K. Sul, and T. Lipo, "AC/AC power conversion based on matrix converter topology with unidirectional switches," *IEEE Trans. Ind. Appl.*, vol. 36, no. 1, pp. 139–145, Jan./Feb. 2000.

[240] C. Liu, B. Wu, Y. Li, and S. Wei, "A novel three-phase PWM rectifier/inverter without capacitor in DC-link," in *Proc. IEEE Int. Conf. Electr. Mach. Syst.*, Oct. 2007, pp. 50–53.

[241] M. E. De Oliveira Filho, J. R. Gazoli, A. J. S. Filho, and E. R. Filho, "A control method for voltage source inverter without dc link capacitor," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 4432–4437.

[242] N. Flourentzou, G. S. Konstantinou, and V. G. Agelidis, "DC-bus capacitorless rectifier-inverter motor drive with online optimized harmonic controlled PWM," in *Proc. IEEE Int. Conf. Ind. Technol.*, Mar. 2010, pp. 344–349.

[243] C. Liu, Z. Sun, N. Cheng, and Y. Li, "A novel synchronous PWM method for three-phase AC/DC/AC converter without DC-link capacitor," in *Proc. 38th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2012, pp. 134–138.

[244] L. Wei and T. Lipo, "A novel matrix converter topology with simple commutation," in *Proc. Conf. Rec. IEEE Ind. Appl. Conf. 36th IAS Annu. Meeting*, vol. 3, Nov. 2002, pp. 1749–1754.

[245] J. Riedemann, I. Andrade, R. Peña, R. Blasco-Gimenez, J. Clare, P. Melín, and M. Rivera, "Modulation strategies for an open-end winding induction machine fed by a two-output indirect matrix converter," *Math. Comput. Simul.*, vol. 130, pp. 95–111, Dec. 2016.

[246] P. C. Loh, F. Blaabjerg, F. Gao, A. Baby, and D. A. C. Tan, "Pulsewidth modulation of neutral-point-clamped indirect matrix converter," *IEEE Trans. Ind. Appl.*, vol. 44, no. 6, pp. 1805–1814, Nov./Dec. 2008.

[247] J. Riedemann, R. Peña, and R. Blasco-Giménez, "Open-end winding induction motor drive based on indirect matrix converter," in *Induction Motors: Applications, Control and Fault Diagnostics*. Rijeka, Croatia: InTech, 2015.

[248] Y. Mei and S. Niu, "The analysis and suppression on the input current harmonics of an indirect matrix converter," in *Proc. 21st Int. Conf. Electr. Mach. Syst. (ICEMS)*, Oct. 2018, pp. 2240–2244.

[249] M. Yang, C. Lisha, L. Wang, and Y. Li, "A model predictive dual current control method for indirect matrix converter fed induction motor drives," in *Proc. Int. Power Electron. Conf. (IPEC-Niigata-ECCE Asia)*, May 2018, pp. 3958–3964.

[250] A. Tsoupos and V. Khadkikar, "A novel SVM technique with enhanced output voltage quality for indirect matrix converters," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 832–841, Feb. 2019.

[251] M. Baumann, F. Stogerer, and J. Kolar, "Part II: Experimental analysis of the very sparse matrix converter," in *Proc. APEC. 17th Annu. IEEE Appl. Power Electron. Conf. Expo.*, vol. 2, Aug. 2005, pp. 788–791.

[252] J. Kolar, M. Baumann, F. Schafmeister, and H. Ertl, "Novel three-phase AC-DC-AC sparse matrix converter," in *Proc. APEC. 17th Annu. IEEE Appl. Power Electron. Conf. Expo.*, vol. 2, Jun. 2003, pp. 777–791.

[253] F. Schafmeister, S. Herold, and J. Kolar, "Evaluation of 1200 V-Si-IGBTs and 1300 V-SiC-JFETs for application in three-phase very sparse matrix AC-AC converter systems," in *Proc. 18th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, vol. 1, Oct. 2003, pp. 241–255.

[254] M. I. Marei, A. Mohy, and A. A. El-Sattar, "An integrated control system for sparse matrix converter interfacing PMSG with the grid," *Int. J. Electr. Power Energy Syst.*, vol. 73, pp. 340–349, Dec. 2015.

[255] N. Taib, B. Metidji, and T. Rekioua, "Performance and efficiency control enhancement of wind power generation system based on DFIG using three-level sparse matrix converter," *Int. J. Electr. Power Energy Syst.*, vol. 53, pp. 287–296, Dec. 2013.

[256] C. N. El-Khoury, H. Y. Kanaan, I. Mougharbel, and K. Al-Haddad, "Optimized modulation technique for series Z-Source Very Sparse Matrix Converter," in *Proc. IEEE 12th Int. Conf. Compat., Power Electron. Power Eng. (CPE-POWERENG)*, Apr. 2018, pp. 1–6.

[257] C. N. El-Khoury, H. Y. Kanaan, I. Mougharbel, and K. Al-Haddad, "Implementation of a series Z-source very sparse matrix converter in a PMSG-based WECS," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Feb. 2018, pp. 20–22.

[258] M. Salem, Y. Atia, and O. Mahgoub, "Ultra sparse matrix rectifier for battery charging application," in *Proc. Int. Conf. Adv. Control Circuits Syst. (ACCS) Syst. Int. Conf. New Paradigms Electron. Inf. Technol. (PEIT)*, Nov. 2017, pp. 305–310.

[259] T. Ghanbari, A. Farjah, E. Bagheri, and M. Raoofat, "Application of Z-source sparse matrix converter for microturbine generators," in *Proc. 9th Annu. Power Electron., Drives Syst. Technol. Conf. (PEDSTC)*, Feb. 2018, pp. 283–288.

[260] A. M. Bozorgi, A. Hakemi, M. Farasat, and M. Monfared, "Modulation techniques for common-mode voltage reduction in the Z-source ultra sparse matrix converters," *IEEE Trans. Power Electron.*, vol. 34, no. 1, pp. 958–970, Jan. 2019.

[261] C. Klumpner, M. Lee, and P. Wheeler, "A new three-level sparse indirect matrix converter," in *Proc. 32nd Annu. Conf. IEEE Ind. Electron. (IECON)*, Nov. 2006, pp. 1902–1907.

[262] M. Yeong Lee, C. Klumpner, and P. Wheeler, "Experimental evaluation of the indirect three-level sparse matrix converter," in *Proc. IET Int. Conf. Power Electron., Mach. Drives (PEMD)*, 2008, pp. 50–54.

[263] S. Raju, L. Srivatchan, V. Chandrasekaran, and N. Mohan, "Constant pulse width modulation strategy for direct three-level matrix converter," in *Proc. IEEE Int. Conf. Power Electron., Drives Energy Syst. (PEDES)*, Dec. 2012, pp. 1–5.

[264] S. Raju and N. Mohan, "Indirect three level matrix converter," in *Proc. IET Int. Conf. Power Electron., Mach. Drives (PEMD)*, 2014, pp. 1–6.

[265] Q. Jianglei, X. Lie, L. Wang, Q. Lin, and L. Yongdong, "The modulation of common mode voltage suppression for a three-level matrix converter," in *Proc. IEEE Int. Conf. Aircr. Utility Syst. (AUS)*, Oct. 2016, pp. 533–538.

[266] A. Benachour, E. M. Berkouk, and M. O. Mahmoudi, "DTC-SVM control of induction machine fed by three level NPC matrix converter," in *Proc. 8th Int. Conf. Modelling, Identificat. Control (ICMIC)*, Nov. 2016, pp. 628–633.

[267] H. Wang, M. Su, Y. Sun, G. Zhang, J. Yang, W. Gui, and J. Feng, "Topology and modulation scheme of a three-level third-harmonic injection indirect matrix converter," *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 7612–7622, Oct. 2017.

[268] Q. Jianglei, X. Lie, W. Lina, and H. Yannia, "Research on the modulation of a three-level matrix converter with reduced common mode voltage," *J. Eng.*, vol. 2018, no. 13, pp. 607–613, Jan. 2018.

[269] M. Leubner, N. Remus, S. Schwarz, and W. Hofmann, "Voltage based 2/3/4-step commutation for direct three-level matrix converter," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2018, pp. P.1–P.10.

[270] B.-H. Kwon, B.-D. Min, and J.-H. Kim, "Novel topologies of AC choppers," *IEE Proc., Electr. Power Appl.*, vol. 143, no. 4, pp. 323–330, 1996.

[271] C. Bing, X. Yunxiang, and T. Fei, "A novel three-phase buck PFC converter based on one-cycle control," in *Proc. Int. Conf. Power Syst. Technol.*, Oct. 2006, pp. 1–7.

[272] S. K. Bassan, D. S. Wijeratne, and G. Moschopoulos, "A three-phase reduced-switch high-power-factor buck-type converter," *IEEE Trans. Power Electron.*, vol. 25, no. 11, pp. 2772–2785, Nov. 2010.

[273] X. Gao, "A study of three-phase APFC based on quadratic buck converter," in *Proc. IEEE PES Innov. Smart Grid Technol.*, May 2012, pp. 1–4.

[274] T. Sopapirm, "Instability mitigation of a three-phase diode rectifier feeding a controlled buck converter by using the active damping method," in *Proc. 21st Int. Conf. Electr. Mach. Syst. (ICEMS)*, Oct. 2018, pp. 745–748.

[275] S. Gangavarapu and A. K. R. Gae, "Three-phase buck–boost derived PFC converter for more electric aircraft," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6264–6275, Jul. 2019.

[276] M. Haider, D. Bortis, J. W. Kolar, and Y. Ono, "Novel sinusoidal input current single-to-three-phase Z-source buck+boost AC/AC converter," in *Proc. Int. Power Electron. Conf. (IPEC-Niigata-ECCE Asia)*, May 2018, pp. 4080–4087.

[277] J. Afsharian, D. D. Xu, B. Wu, B. Gong, Z. Yang, and J.-I. Itoh, "Analysis of one phase loss operation of three-phase isolated buck matrix-type rectifier with eight-segment PWM scheme," in *Proc. Int. Power Electron. Conf. (IPEC-Niigata-ECCE Asia)*, May 2018, pp. 3797–3804.

[278] P. S. Huynh, D. Vincent, N. A. Azeez, L. Patnaik, and S. S. Williamson, "Performance analysis of a single-stage high-frequency AC-AC buck converter for a series-series compensated inductive power transfer system," in *Proc. IEEE Transp. Electrific. Conf. Expo (ITEC)*, Jun. 2018, pp. 347–352.

[279] G. Roy and G.-E. April, "Direct frequency changer operation under a new scalar control algorithm," *IEEE Trans. Power Electron.*, vol. 6, no. 1, pp. 100–107, Jan. 1991.

[280] P. Kulkarni, M. Tewolde Abraham, and S. P. Das, "Design and simulation of a matrix converter-fed scalar controlled synchronous motor drive," in *Proc. Annu. IEEE India Conf.*, vol. 1, Dec. 2008, pp. 69–74.

[281] V. I. Popov and E. D. Baranov, "Scalar modulation control technique for modular multilevel matrix converter," in *Proc. 14th Int. Conf. Young Spec. Micro/Nanotechnologies Electron Devices*, Jul. 2013, pp. 261–264.

[282] J. Rodriguez, "High performance DC motor drive using a PWM rectifier with power transistors," *IEE Proc. B—Electr. Power Appl.*, vol. 134, no. 1, pp. 1–9, Jan. 1987.

[283] N. P. R. Iyer, "Carrier based modulation technique for three phase matrix converters–state of the art progress," in *Proc. IEEE Region 8 Int. Conf. Comput. Technol. Electr. Electron. Eng. (SIBIRCON)*, Jul. 2010, pp. 659–664.

[284] P. Kiatsookkanatorn and S. Sangwongwanich, "A unified PWM method for matrix converters and its carrier-based realization using dipolar modulation technique," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 80–92, Jan. 2012.

[285] F. Gruson, P. Le Moigne, P. Delarue, A. Videt, X. Cimetiere, and M. Arpilliere, "A simple carrier-based modulation for the SVM of the matrix converter," *IEEE Trans. Ind. Inf.*, vol. 9, no. 2, pp. 947–956, May 2013.

[286] M. Banaei and E. Salary, "Mitigation of voltage sag, swell and power factor correction using solid-state transformer based matrix converter in output stage," *Alexandria Eng. J.*, vol. 53, no. 3, pp. 563–572, Sep. 2014.

[287] R. Baranwal, K. Basu, and N. Mohan, "Carrier-based implementation of SVPWM for dual two-level VSI and dual matrix converter with zero common-mode voltage," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1471–1487, Mar. 2015.

[288] C. Piao and J. Y. Hung, "A unified carrier-based modulation method for direct matrix converter," in *Proc. IEEE Int. Conf. Electro/Inf. Technol. (EIT)*, May 2015, pp. 122–128.

[289] P. S. Prasad, A. B. V. S. Kumar, and G. S. Rao, "Induction motor speed control by carrier modulation based matrix converter," in *Proc. Int. Conf. Signal Process., Commun., Power Embedded Syst. (SCOPES)*, Oct. 2016, pp. 1176–1180.

[290] L. Wang, H. Wang, M. Su, Y. Sun, J. Yang, M. Dong, X. Li, W. Gui, and J. Feng, "A three-level T-type indirect matrix converter based on the third-harmonic injection technique," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 5, no. 2, pp. 841–853, Jun. 2017.

[291] P. Kiatsookkanatorn and S. Sangwongwanich, "Carrier-based overmodulation strategy for matrix converters," in *Proc. Int. Power Electron. Conf. (IPEC-Niigata-ECCE Asia)*, May 2018, pp. 2581–2588.

[292] T.-L. Lee, C.-Y. Hung, Y.-W. Chen, and W.-M. Huang, "Fixed slope carrier PWM for indirect matrix converter," in *Proc. Int. Power Electron. Conf. (IPEC-Niigata-ECCE Asia)*, May 2018, pp. 2576–2580.

[293] D. Casadei, G. Serra, A. Tani, and L. Zarri, "Matrix converter modulation strategies: A new general approach based on space-vector representation of the switch state," *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 370–381, Apr. 2002.

[294] M. Jussila and H. Tuusa, "Semiconductor power loss comparison of space-vector modulated direct and indirect matrix converter," in *Proc. Power Convers. Conf.-Nagoya*, Apr. 2007, pp. 831–838.

[295] F. Gao and M. R. Iravani, "Dynamic model of a space vector modulated matrix converter," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1696–1705, Jul. 2007.

[296] J. Vadillo, J. M. Echeverria, A. Galarza, and L. Fontan, "Modelling and simulation of space vector modulation techniques for matrix converters: Analysis of different switching strategies," in *Proc. Int. Conf. Electr. Mach. Syst.*, Oct. 2008, pp. 1299–1304.

[297] G. Li, K. Sun, and L. Huang, "A novel algorithm for space vector modulated two-stage matrix converter," in *Proc. Int. Conf. Electr. Mach. Syst.*, Oct. 2008, pp. 1316–1320.

[298] M. Y. Lee, P. Wheeler, and C. Klumpner, "Space-vector modulated multilevel matrix converter," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3385–3394, Oct. 2010.

[299] D. Shaowu, Y. Zhang, X. Meng, and A. Zhong, "Selecting the carrier frequency for two-stage matrix converter based on dual space vector and dual carrier modulation," in *Proc. 2nd Int. Symp. Power Electron. Distrib. Gener. Syst.*, Jun. 2010, pp. 129–132.

[300] N. Holtsmark and M. Molinas, "Reactive power compensation using an indirectly space vector-modulated matrix converter," in *Proc. IEEE Int. Symp. Ind. Electron.*, Jul. 2010, pp. 2455–2460.

[301] B. Cai and J. Zhu, "Direct torque control for induction machine based on space vector modulated matrix converters," in *Proc. 2nd Int. Workshop Database Technol. Appl.*, Nov. 2010, pp. 1–4.

[302] N. Khanh Tu Tam, N. Van Nho, and H. Thai Hoang, "Indirect space vector modulated three phase ac-ac matrix converter under abnormal input conditions," in *Proc. IEEE 9th Int. Conf. Power Electron. Drive Syst.*, Dec. 2011, pp. 379–384.

[303] H. She, H. Lin, B. He, X. Wang, L. Yue, and X. An, "Implementation of voltage-based commutation in space-vector-modulated matrix converter," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 154–166, Jan. 2012.

[304] S. Kwak, "Four-leg-based fault-tolerant matrix converter schemes based on switching function and space vector methods," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 235–243, Jan. 2012.

[305] B. Feng, H. Lin, X. Wang, X. An, and B. Liu, "Optimal zero-vector configuration for space vector modulated AC-DC matrix converter," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2012, pp. 291–297.

[306] S. Dabour and E. Rashad, "Analysis and implementation of space-vector-modulated three-phase matrix converter," *IET Pwr. Electr.*, vol. 5, no. 8, pp. 1374–1378, 2012.

[307] S. Raju, L. Srivatchan, and N. Mohan, "Direct space vector modulated three level matrix converter," in *Proc. 28th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2013, pp. 475–481.

[308] S. Raju and N. Mohan, "Space vector modulated hybrid indirect multilevel matrix converter," in *Proc. 39th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2013, pp. 4931–4936.

[309] B. Zhou, Y. Mo, W. Jiang, S. Finney, and B. W. Williams, "A linear equation solution space based control algorithm for the matrix converter," in *Proc. 39th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2013, pp. 4818–4823.

[310] A. M. Bozorgi, M. Monfared, and H. R. Mashhadi, "Two simple overmodulation algorithms for space vector modulated three-phase to three-phase matrix converter," *IET Power Electron.*, vol. 7, no. 7, pp. 1915–1924, Jul. 2014.

[311] B. Cai and X. Nian, "Direct torque control drived by matrix converter based on space vector modulated," in *Proc. 33rd Chin. Control Conf.*, Jul. 2014, pp. 8017–8020.

[312] S. M. Ahmed, H. Abu-Rub, and Z. Salam, "Space vector control of dual matrix converters based five-phase open-end winding drive," in *Proc. IEEE Conf. Energy Convers. (CENCON)*, Oct. 2014, pp. 348–353.

[313] S. Pinto, P. Mendes, and J. F. Silva, "Modular matrix converter based solid state transformer for smart grids," *Electr. Power Syst. Res.*, vol. 136, pp. 189–200, Jul. 2016.

[314] S. M. Dabour, A. S. Abdel-Khalik, S. Ahmed, A. M. Massoud, and S. Allam, "Common-mode voltage reduction for space vector modulated three- to five-phase indirect matrix converter," *Int. J. Electr. Power Energy Syst.*, vol. 95, pp. 266–274, Feb. 2018.

[315] S. M. Ahmed, H. Abu-Rub, and Z. Salam, "Common-mode voltage elimination in a three-to-five-phase dual matrix converter feeding a five-phase open-end drive using space-vector modulation technique," *IEEE Trans. Ind. Electron.*, vol. 62, no. 10, pp. 6051–6063, Oct. 2015.

[316] P. Patel and M. A. Mulla, "Space vector modulated three-phase to three-phase direct matrix converter," in *Proc. IEEE 16th Int. Conf. Environ. Electr. Eng. (EEEIC)*, Jun. 2016, pp. 1–6.

[317] X. Ma, S. Zhang, and J. Zhao, "Improved active disturbance rejection control strategy for space-vector-modulated matrix converter," in *Proc. 6th Data Driven Control Learn. Syst. (DDCLS)*, May 2017, pp. 323–329.

[318] T. Shi, L. Wu, Y. Yan, and C. Xia, "Harmonic spectrum of output voltage for space vector-modulated matrix converter based on triple fourier series," *IEEE Trans. Power Electron.*, vol. 33, no. 12, pp. 10646–10653, Dec. 2018.

[319] A. M. Bozorgi and M. Farasat, "Improved design and space vector modulation of a Z-source ultrasparse matrix converter: Analysis, implementation, and performance evaluation," *IEEE Trans. Ind. Appl.*, vol. 54, no. 4, pp. 3737–3748, Jul. 2018.

[320] Q. Lin, X. Lie, L. Yongdong, H. Xiaoyan, and F. Youtong, "Spectral analysis of a SVPWM modulated matrix converter based on 3D Fourier integral," *J. Eng.*, vol. 2018, no. 13, pp. 411–416, Jan. 2018.

[321] S. Arya and G. K. Nisha, "Indirect space vector modulation based three phase matrix converter," in *Proc. Int. CET Conf. Control, Commun., Comput. (IC4)*, Jul. 2018, pp. 68–73.

[322] S. Muller, U. Ammann, and S. Rees, "New time-discrete modulation scheme for matrix converters," *IEEE Trans. Ind. Electron.*, vol. 52, no. 6, pp. 1607–1615, Dec. 2005.

[323] T. Wijekoon, C. Klumpner, P. Zanchetta, and P. Wheeler, "A predictive current control scheme for a hybrid AC/AC direct power converter," in *Proc. IET Int. Conf. Power Electron., Mach. Drives (PEMD)*, 2006, pp. 1–6.

[324] P. Gamboa, S. F. Pinto, J. F. Silva, and E. Margato, "Predictive optimal control of input and output currents in matrix converters," in *Proc. Int. Conf. Power Eng., Energy Electr. Drives*, Apr. 2007, pp. 529–533.

[325] M. Rivera, R. Vargas, J. Espinoza, J. Rodriguez, P. Wheeler, and C. Silva, "Current control in matrix converters connected to polluted AC voltage supplies," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 412–417.

[326] R. Vargas, J. Rodriguez, U. Ammann, and P. Wheeler, "Predictive current control of an induction machine fed by a matrix converter with reactive power control," *IEEE Trans. Ind. Electron.*, vol. 55, no. 12, pp. 4362–4371, Dec. 2008.

[327] Y. Li, N.-S. Choi, H. Cha, and F. Peng, "Carrier-based predictive current controlled pulse width modulation for matrix converters," in *Proc. IEEE 6th Int. Power Electron. Motion Control Conf.*, May 2009, pp. 1009–1014.

[328] J. Rodriguez, J. Kolar, J. Espinoza, M. Rivera, and C. Rojas, "Predictive current control with reactive power minimization in an indirect matrix converter," in *Proc. IEEE Int. Conf. Ind. Technol.*, 2010, pp. 1839–1844.

[329] R. Vargas, J. Rodriguez, C. Rojas, and P. Wheeler, "Predictive current control applied to a matrix converter: An assessment with the direct transfer function approach," in *Proc. IEEE Int. Conf. Ind. Technol.*, Mar. 2010, pp. 1832–1838.

[330] J. Rodriguez, J. Espinoza, M. Rivera, F. Villarroel, and C. Rojas, "Predictive control of source and load currents in a direct matrix converter," in *Proc. IEEE Int. Conf. Ind. Technol.*, Mar. 2010, pp. 1826–1831.

[331] M. Rivera, C. Rojas, J. Rodríguez, P. Wheeler, B. Wu, and J. Espinoza, "Predictive current control with input filter resonance mitigation for a direct matrix converter," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2794–2803, Oct. 2011.

[332] M. Rivera, J. Rodriguez, B. Wu, J. R. Espinoza, and C. A. Rojas, "Current control for an indirect matrix converter with filter resonance mitigation," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 71–79, Jan. 2012.

[333] M. Rivera, J. Rodriguez, P. W. Wheeler, C. A. Rojas, A. Wilson, and J. R. Espinoza, "Control of a matrix converter with imposed sinusoidal source currents," *IEEE Trans. Ind. Electron.*, vol. 59, no. 4, pp. 1939–1949, Apr. 2012.

[334] M. Rivera, J. Rodriguez, J. R. Espinoza, and H. Abu-Rub, "Instantaneous reactive power minimization and current control for an indirect matrix converter under a distorted AC supply," *IEEE Trans. Ind. Inf.*, vol. 8, no. 3, pp. 482–490, Aug. 2012.

[335] E. Lee, K.-B. Lee, J.-S. Lim, Y. Lee, and J.-H. Song, "Predictive current control for a sparse matrix converter," in *Proc. 7th Int. Power Electron. Motion Control Conf.*, vol. 1, Jun. 2012, pp. 36–40.

[336] M. Rivera, A. Wilson, C. A. Rojas, J. Rodriguez, J. R. Espinoza, P. W. Wheeler, and L. Empringham, "A comparative assessment of model predictive current control and space vector modulation in a direct matrix converter," *IEEE Trans. Ind. Electron.*, vol. 60, no. 2, pp. 578–588, Feb. 2013.

[337] M. Rivera, J. Rodriguez, C. Rojas, and J. Espinoza, "Methods of source current reference generation for predictive control in a direct matrix converter," *IET Power Electron.*, vol. 6, no. 5, pp. 894–901, May 2013.

[338] M. Rivera, J. Munoz, C. Baier, J. Rodriguez, J. Espinoza, V. Yaramasu, B. Wu, and P. Wheeler, "A simple predictive current control of a single-phase matrix converter," in *Proc. Int. Conf. Power Eng., Energy Electr. Drives*, May 2013, pp. 235–239.

[339] M. Rivera, J. Rodriguez, J. Espinoza, J. Muñoz, C. Baier, A. Wilson, and C. Rojas, "Review of predictive control methods to improve the input current of an indirect matrix converter," *IET Power Electron.*, vol. 7, no. 4, pp. 886–894, Apr. 2014.

[340] J. L. Elizondo, A. Olloqui, M. Rivera, M. E. Macias, O. Probst, O. M. Micheloud, and J. Rodriguez, "Model-based predictive rotor current control for grid synchronization of a DFIG driven by an indirect matrix converter," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 4, pp. 715–726, Dec. 2014.

[341] C. Hackl, "MPC with analytical solution and integral error feedback for LTI MIMO systems and its application to current control of grid-connected power converters with LCL-filter," in *Proc. IEEE Int. Symp. Predictive Control Electr. Drives Power Electron. (PRECEDE)*, Oct. 2015, pp. 61–66.

[342] M. Vijayagopal, P. Zanchetta, L. Empringham, L. De Lillo, L. Tarisciotti, and P. Wheeler, "Modulated model predictive current control for direct matrix converter with fixed switching frequency," in *Proc. 17th Eur. Conf. Power Electron. Appl. (EPE ECCE-Eur.)*, Sep. 2015, pp. 1–10.

[343] M. Rivera, "Predictive control with imposed sinusoidal source and load currents of an indirect matrix converter operating at fixed switching frequency and without weighting factors," in *Proc. IEEE 5th Int. Conf. Power Eng., Energy Electr. Drives (POWERENG)*, May 2015, pp. 641–647.

[344] A. Olloqui, J. L. Elizondo, M. Rivera, M. E. Macias, O. M. Micheloud, R. Pena, and P. Wheeler, "Indirect power control of a DFIG using model-based predictive rotor current control with an indirect matrix converter," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2015, pp. 2275–2280.

[345] O. Gulbudak, J. Marquart, and E. Santi, "FPGA-based model predictive current controller for 3×3 direct matrix converter," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2015, pp. 4307–4314.

[346] H. Han, Z. Tang, G. Zhang, X. Li, and Q. Zhu, "Model predictive current control of third-harmonic injection two-stage matrix converter," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Oct. 2016, pp. 561–565.

[347] M. Rivera, P. Wheeler, and A. Olloqui, "Predictive control in matrix converters—Part I: Principles, topologies and applications," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2016, pp. 1091–1097.

[348] M. Rivera, P. Wheeler, and A. Olloqui, "Predictive control in matrix converters—Part II: Control strategies, weaknesses and trends," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2016, pp. 1098–1104.

[349] T. Peng, H. Dan, J. Yang, H. Deng, Q. Zhu, C. Wang, W. Gui, and J. M. Guerrero, "Open-switch fault diagnosis and fault tolerant for matrix converter with finite control set-model predictive control," *IEEE Trans. Ind. Electron.*, vol. 63, no. 9, pp. 5953–5963, Sep. 2016.

[350] M. Rivera, U. Nasir, L. Tarisciotti, and P. Wheeler, "Indirect model predictive current control techniaues for a direct matrix converter," in *Proc. IEEE URUCON*, Oct. 2017, pp. 1–4.

[351] M. Siami, D. A. Khaburi, M. Rivera, and J. Rodriguez, "An experimental evaluation of predictive current control and predictive torque control for a PMSM fed by a matrix converter," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8459–8471, Nov. 2017.

[352] C. F. Garcia, M. E. Rivera, J. R. Rodriguez, P. W. Wheeler, and R. S. Pena, "Predictive current control with instantaneous reactive power minimization for a four-leg indirect matrix converter," *IEEE Trans. Ind. Electron.*, vol. 64, no. 2, pp. 922–929, Feb. 2017.

[353] Z. Tang, H. Han, M. Su, X. Li, B. Guo, and H. Wang, "Current control for third-harmonic injection two-stage matrix converter under unbalanced input voltages," in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2017, pp. 7091–7096.

[354] S. Toledo, E. Maqueda, M. Rivera, R. Gregor, D. Caballero, F. Gavilan, and J. Rodas, "Experimental assessment of IGBT and SiC-MOSFET based technologies for matrix converter using predictive current control," in *Proc. Conf. Electr., Electron. Eng., Inf. Commun. Technol. (CHILECON)*, Oct. 2017, pp. 1–6.

[355] P. Wheeler, M. Rivera, and S. Toledo, "An indirect model predictive current control for a direct matrix converter with instantaneous reactive power minimization," in *Proc. IEEE Southern Power Electron. Conf. (SPEC)*, Dec. 2017, pp. 1–6.

[356] H. Mohamed Basri and S. Mekhilef, "Experimental evaluation of model predictive current control for a modified three-level four-leg indirect matrix converter," *IET Electr. Power Appl.*, vol. 12, no. 1, pp. 114–123, Jan. 2018.

[357] G. F. Gontijo, T. C. Tricarico, B. W. Franca, L. F. Da Silva, E. L. Van Emmerik, and M. Aredes, "Robust model predictive rotor current control of a DFIG connected to a distorted and unbalanced grid driven by a direct matrix converter," *IEEE Trans. Sustain. Energy*, vol. 10, no. 3, pp. 1380–1392, Jul. 2019.

[358] M. Roostaee, B. Eskandari, and M. R. Azizi, ''Predictive current control with modification of instantaneous reactive power minimization for direct matrix converter,'' in *Proc. 9th Annu. Power Electron., Drives Syst. Technol. Conf. (PEDSTC)*, Feb. 2018, pp. 199–205.

[359] M. E. Rivera, R. E. Vargas, J. R. Espinoza, and J. R. Rodriguez, ''Behavior of the predictive DTC based matrix converter under unbalanced AC supply,'' in *Proc. IEEE Ind. Appl. Annu. Meeting*, Sep. 2007, pp. 202–207.

[360] J. Rodriguez, J. Pontt, R. Vargas, P. Lezana, U. Ammann, P. Wheeler, and F. Garcia, ''Predictive direct torque control of an induction motor fed by a matrix converter,'' in *Proc. Eur. Conf. Power Electron. Appl.*, 2007, pp. 1–10.

[361] S. A. Davari, F. Montazeri, F. Montazeri, and D. A. Khaburi, ''A comparative study of matrix converter based DTC with complete vectors application and an improved predictive torque control using two-level inverter,'' in *Proc. IEEE Int. Conf. Electr. Electron. Eng.*, Nov. 2009, p. I-410.

[362] C. Ortega, A. Arias, and J. Espina, ''Predictive vector selector for direct torque control of matrix converter fed induction motors,'' in *Proc. 35th Annu. Conf. IEEE Ind. Electron.*, Nov. 2009, pp. 1240–1245.

[363] R. Vargas, U. Ammann, B. Hudoffsky, J. Rodriguez, and P. Wheeler, ''Predictive torque control of an induction machine fed by a matrix converter with reactive input power control,'' *IEEE Trans. Power Electron.*, vol. 25, no. 6, pp. 1426–1438, Jun. 2010.

[364] M. Lopez, M. Rivera, C. Garcia, J. Rodriguez, R. Pena, J. Espinoza, and P. Wheeler, ''Predictive torque control of a multi-drive system fed by a six-leg indirect matrix converter,'' in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Feb. 2013, pp. 1642–1647.

[365] L. Zakaria and K. Barra, ''Predictive direct torque and flux control of an induction motor drive fed by a direct matrix converter with reactive power minimization,'' in *Proc. 10th IEEE Int. Conf. Netw., Sens. Control (ICNSC)*, Apr. 2013, pp. 34–39.

[366] Y. Yan, T. Shi, C. Xia, and J. Zhao, ''Direct torque control of matrix converter-fed permanent magnet synchronous motor drives based on master and slave vectors,'' *IET Power Electron.*, vol. 8, no. 2, pp. 288–296, Feb. 2015.

[367] M. Siami, D. A. Khaburi, M. Yousefi, and J. Rodriguez, ''Improved predictive torque control of a permanent magnet synchronous motor fed by a matrix converter,'' in *Proc. 6th Power Electron., Drive Syst. Technol. Conf. (PEDSTC)*, Feb. 2015, pp. 369–374.

[368] M. Siami, H. K. Savadkoohi, A. Abbaszadeh, D. A. Khaburi, J. Rodriguez, and M. Rivera, ''Predictive torque control of a permanent magnet synchronous motor fed by a matrix converter without weighting factor,'' in *Proc. 7th Power Electron. Drive Syst. Technol. Conf. (PEDSTC)*, Feb. 2016, pp. 614–619.

[369] M. Lopez, J. Rodriguez, C. Silva, and M. Rivera, ''Predictive torque control of a multidrive system fed by a dual indirect matrix converter,'' *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 2731–2741, May 2015.

[370] S. Bayhan, P. Kakosimos, and M. Rivera, ''Predictive torque control of brushless doubly fed induction generator fed by a matrix converter,'' in *Proc. IEEE 12th Int. Conf. Compat., Power Electron. Power Eng. (CPE-POWERENG)*, Apr. 2018, pp. 1–6.

[371] D. Casadei, G. Serra, and A. Tani, ''The use of matrix converters in direct torque control of induction machines,'' in *Proc. Annu. Conf. IEEE Ind. Electron. Soc.*, vol. 2, Aug./Sep. 1998, pp. 744–749.

[372] D. Casadei, G. Serra, and A. Tani, ''The use of matrix converters in direct torque control of induction machines,'' *IEEE Trans. Ind. Electron.*, vol. 48, no. 6, pp. 1057–1064, Dec. 2001.

[373] H.-H. Lee and M.-H. Nguyen, ''Matrix converter fed induction motor using a new modified direct torque control method,'' in *Proc. Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, vol. 3, May 2005, pp. 2301–2306.

[374] C. Ortega, A. Arias, J. Romeral, and E. Aldabas, ''Direct torque control for induction motors using matrix converters,'' in *Proc. IEEE Compat. Power Electron.*, Dec. 2005, pp. 53–60.

[375] C. Ortega, A. Arias, X. Del Toro, E. Aldabas, and J. Balcells, ''Novel direct torque control for induction motors using short voltage vectors of matrix converters,'' in *Proc. Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, 2005, p. 6.

[376] P. Quoc Dzung and L. Minh Phuong, ''A new artificial neural network-Direct torque control for matrix converter fed three-phase induction motor,'' in *Proc. Int. Conf. Power Electron. Drives Syst.*, vol. 1, Apr. 2006, pp. 78–83.

[377] X. Chen and M. Kazerani, ''A new direct torque control strategy for induction machine based on indirect matrix converter,'' in *Proc. IEEE Int. Symp. Ind. Electron.*, vol. 3, Jul. 2006, pp. 2479–2484.

[378] B. Singh and J. Ravi, ''Modified direct torque control of matrix converter fed induction motor drive,'' in *Proc. Int. Conf. Power Electron., Drives Energy Syst.*, Dec. 2006, pp. 1–7.

[379] S. Zhang-hai and K. W. E. Cheng, ''Simulation research of the matrix converter based on direct torque control,'' in *Proc. 2nd Int. Conf. Power Electron. Syst. Appl.*, Nov. 2006, pp. 199–204.

[380] R. A. Gupta, R. Kumar, and V. Sangtani, ''Direct torque controlled matrix converter fed induction motor drive,'' in *Proc. Int. Conf. Circuits, Power Comput. Technol. (ICCPCT)*, Mar. 2014, pp. 698–703.

[381] R. Muthu, M. S. Kumaran, L. A. Rajaraman, P. Ganesh, and P. G. P. Reddy, ''Direct torque control of matrix converter fed BLDC motor,'' in *Proc. IEEE 6th India Int. Conf. Power Electron. (IICPE)*, Dec. 2014, pp. 1–6.

[382] S. Mondal and D. Kastha, ''Improved direct torque and reactive power control of a matrix-converter-fed grid-connected doubly fed induction generator,'' *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7590–7598, Dec. 2015.

[383] S. Kannan and S. Prabha, ''Torque ripple minimization of Matrix Converter-fed PMSM drives using Model Predictive Torque Control,'' in *Proc. IEEE 9th Int. Conf. Intell. Syst. Control (ISCO)*, Jan. 2015, pp. 1–9.

[384] M. R. Barzegaran, M. Kamruzzaman, H. Mahmud, and O. A. Mohammed, ''Direct torque control of permanent magnet synchronous machine using Sparse matrix converter with SiC switches,'' in *Proc. IEEE Int. Electr. Mach. Drives Conf. (IEMDC)*, May 2015, pp. 1683–1688.

[385] M. Madaci, D. Kerdoun, and N. Cherfia, ''MPC-DTC indirect matrix converter with switches optimization and FPGA based control technique implementation for crane mechanical system,'' in *Proc. 4th Int. Conf. Control Eng. Inf. Technol. (CEIT)*, Dec. 2016, pp. 1–8.

[386] J. Wang, X. Y. Huang, Y. T. Fang, Q. F. Lu, H. Yang, and Y. Q. Gao, ''A fault-tolerant direct torque control strategy for a brushless dc motor driven by a single sided matrix converter,'' in *Proc. 19th Int. Conf. Electr. Mach. Syst.*, Nov. 2016, pp. 1–5.

[387] I. Kozakevich, ''Investigation of the direct torque control system of an electromechanical system with a matrix converter,'' in *Proc. Int. Conf. Mod. Electr. Energy Syst. (MEES)*, Nov. 2017, pp. 228–231.

[388] J. Wang, X. Huang, S. Zhao, and Y. Fang, ''Direct torque control for brushless DC motors in aerospace applications with single sided matrix converters with reduced torque ripple,'' in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2017, pp. 4143–4149.

[389] J. Zhang, L. Li, D. Dorrell, and Y. Guo, ''Direct torque control with a modified switching table for a direct matrix converter based AC motor drive system,'' in *Proc. 20th Int. Conf. Electr. Mach. Syst. (ICEMS)*, Aug. 2017, pp. 1–6.

[390] N. Fazli and J. Siahbalaee, ''Direct torque control of a wind energy conversion system with permanent magnet synchronous generator and Matrix Converter,'' in *Proc. 8th Power Electron., Drive Syst. Technol. Conf. (PEDSTC)*, 2017, pp. 166–171.

[391] P. Siwek, ''Input filter optimisation for a DTC driven matrix converter-fed PMSM drive,'' in *Proc. 23rd Int. Conf. Methods Models Autom. Robot. (MMAR)*, Aug. 2018, pp. 35–40.

[392] Y. Guo, X. Wang, Y. Guo, and W. Deng, ''Speed-sensorless direct torque control scheme for matrix converter driven induction motor,'' *J. Eng.*, vol. 2018, no. 13, pp. 432–437, Jan. 2018.

[393] H. H. Lee, P. Q. Dzung, L. M. Phuong, and L. D. Khoa, ''A new artificial neural network controller for direct control method for matrix converters,'' in *Proc. Int. Conf. Power Electron. Drive Syst. (PEDS)*, Nov. 2009, pp. 434–439.

[394] C. Venugopal, ''ANFIS based field oriented control for matrix converter fed induction motor,'' in *Proc. IEEE Int. Conf. Power Energy*, Nov. 2010, pp. 74–78.

[395] H. Karaca, R. Akkaya, and H. Dogan, ''A novel compensation method based on fuzzy logic control for matrix converter under distorted input voltage conditions,'' in *Proc. 18th Int. Conf. Electr. Mach.*, Sep. 2008, pp. 1–5.

[396] K. Park, E.-S. Lee, and K.-B. Lee, ''A Z-source sparse matrix converter with a fuzzy logic controller based compensation method under abnormal input voltage conditions,'' in *Proc. IEEE Int. Symp. Ind. Electron.*, Jul. 2010, pp. 614–619.

[397] C. F. Calvillo, F. Martell, J. L. Elizondo, A. Avila, M. E. Macias, M. Rivera, and J. Rodriguez, ''Rotor current fuzzy control of a DFIG with an indirect matrix converter,'' in *Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2011, pp. 4296–4301.

[398] F. Villarroel, J. Espinoza, C. Rojas, C. Molina, and J. Rodriguez, "Application of fuzzy decision making to the switching state selection in the predictive control of a direct matrix converter," in *Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2011, pp. 4272–4277.
[399] C. Venugopal, "Fuzzy logic based DTC for speed control of matrix converter fed induction motor," in *Proc. IEEE Int. Conf. Power Energy*, Nov. 2010, pp. 753–758.
[400] A. Boukadoum, T. Bahi, S. Oudina, Y. Souf, and S. Lekhchine, "Fuzzy control adaptive of a matrix converter for harmonic compensation caused by nonlinear loads," *Energy Procedia*, vol. 18, pp. 715–723, 2012.
[401] C. F. Calvillo, A. Olloqui, F. Martell, J. L. Elizondo, A. Avila, M. E. Macias, M. Rivera, and J. Rodriguez, "Comparison of model based predictive control and fuzzy logic control of a DFIG with an indirect matrix converter," in *Proc. 38th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2012, pp. 6063–6068.
[402] C. Shankar, N. Sundaram, and R. Thottungal, "Unified power flow controller with matrix converter: Performance evaluation with fuzzy logic control," in *Proc. IET Chennai 4th Int. Conf. Sustain. Energy Intell. Syst. (SEISCON)*, 2013, pp. 254–258.
[403] F. Villarroel, J. R. Espinoza, C. A. Rojas, J. Rodriguez, M. Rivera, and D. Sbarbaro, "Multiobjective switching state selector for finite-states model predictive control based on fuzzy decision making in a matrix converter," *IEEE Trans. Ind. Electron.*, vol. 60, no. 2, pp. 589–599, Feb. 2013.
[404] A. Khodamoradi, H. K. Kargar, and A. Nateghi, "Fuzzy logic control of matrix-converter-based WECS in order to performance improvement," in *Proc. 22nd Iranian Conf. Electr. Eng. (ICEE)*, May 2014, pp. 713–718.
[405] B. M. Faizal, K. Kandan, R. Dhivya, and N. Elayaraja, "Analysis of output current of matrix converter with fuzzy controller," in *Proc. 2nd Int. Conf. Current Trends In Eng. Technol. (ICCTET)*, Jul. 2014, pp. 156–162.
[406] B. Hamane, M. L. Doumbia, A. Cheriti, and K. Belmokhtar, "Comparative analysis of PI and fuzzy logic controllers for matrix converter," in *Proc. 9th Int. Conf. Ecological Vehicles Renew. Energies (EVER)*, Mar. 2014, pp. 1–7.
[407] C. Udhayashankar, R. Thottungal, and N. M. Sundaram, "Matrix converter based UPFC for transient stability enhancement using Fuzzy Logic Control," in *Proc. Int. Conf. Adv. Electr. Eng. (ICAEE)*, Jan. 2014, pp. 1–4.
[408] Y. B. Yakut, S. Sunter, and M. Ozdemir, "Comparation of PI and Neural Fuzzy based closed loop control methods for permanent magnet synchronous motor fed by matrix converter," in *Proc. Int. Aegean Conf. Electr. Mach. Power Electron. (ACEMP), Int. Conf. Optim. Electr. Electron. Equip. (OPTIM) Int. Symp. Adv. Electromech. Motion Syst. (ELECTROMOTION)*, Sep. 2015, pp. 399–405.
[409] R. B. Roy, J. Cros, E. Basher, and S. M. B. Taslim, "Fuzzy logic based matrix converter controlled indution motor drive," in *Proc. IEEE Region 10 Humanitarian Technol. Conf. (R10-HTC)*, Dec. 2017, pp. 489–493.
[410] N. Lavanya, O. C. Sekhar, and M. Ramamoorty, "Performance of indirect matrix converter with improved control feeding to induction motor for speed control by using PI and fuzzy controllers," in *Proc. IEEE Region 10 Conf. (TENCON)*, Nov. 2017, pp. 309–314.
[411] P. Magesh and G. P. Ramesh, "Fuzzy logic control implementation of ultra sparse matrix converter for renewable energy applications," in *Proc. Int. Conf. Inf. Commun. Embedded Syst. (ICICES)*, Feb. 2017, pp. 1–3.
[412] D. Sri Vidhya and T. Venkatesan, "Quasi-Z-source indirect matrix converter fed induction motor drive for flow control of dye in paper mill," *IEEE Trans. Power Electron.*, vol. 33, no. 2, pp. 1476–1486, Feb. 2018.
[413] M. Ali, M. R. Khan, and M. Ayyub, "Analysis of three-phase input to five-phase output matrix converter using direct transfer function approach," in *Proc. Int. Conf. Recent Develop. Control, Autom. Power Eng. (RDCAPE)*, Mar. 2015, pp. 161–166.
[414] M. Dusseault, J. Gagnon, D. Galibois, M. Granger, D. McNabb, D. Nadeau, J. Primeau, S. Fiset, E. Larsen, and G. Drobniak, "First VFT application and commissioning," *Canada Power*, pp. 28–30, Sep. 2004.
[415] A. Merkhouf, P. Doyon, and S. Upadhyay, "Variable frequency transformer—Concept and electromagnetic design evaluation," *IEEE Trans. Energy Convers.*, vol. 23, no. 4, pp. 989–996, Dec. 2008.
[416] P. E. Marken, J. J. Marczewski, R. D'Aquila, P. Hassink, J. H. Roedel, and R. L. Bodo, "VFT- A smart transmission technology that is compatible with the existing and future grid," in *Proc. IEEE Power Syst. Conf. Expo.*, 2009, pp. 1–7.
[417] B. B. Ambati, P. Kanjiya, V. Khadkikar, M. S. El Moursi, and J. L. Kirtley, "A hierarchical control strategy with fault ride-through capability for variable frequency transformer," *IEEE Trans. Energy Convers.*, vol. 30, no. 1, pp. 132–141, Mar. 2015.
[418] R. Rahul, A. K. Jain, and R. Bhide, "Analysis of variable frequency transformer used in power transfer between asynchronous grids," in *Proc. IEEE Int. Conf. Power Electron., Drives Energy Syst. (PEDES)*, Dec. 2012, pp. 1–5.
[419] G. Chen and X. Zhou, "Digital simulation of variable frequency transformers for asynchronous interconnection in power system," in *Proc. IEEE/PES Transmiss. Distribution Conf. Expo., Asia Pacific*, Dec. 2005, pp. 1–6.
[420] L. Contreras-Aguilar and N. Garcia, "Steady-state solution of a VFT park using the limit cycle method and a reduced order model," in *Proc. IEEE Bucharest PowerTech*, Jun. 2009, pp. 1–6.
[421] L. Contreras-Aguilar and N. Garcia, "Fast convergence to the steady-state operating point of a VFT park using the limit cycle method and a reduced order model," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2009, pp. 1–5.
[422] E. T. Raslan, A. S. Abdel-Khalik, M. A. Abdulla, and M. Z. Mustafa, "Performance of VFT when connecting two power grids operating under different frequencies," in *Proc. 5th IET Int. Conf. Power Electron., Mach. Drives (PEMD)*, Apr. 2010, pp. 1–6.
[423] A. H. El Din, M. Ashraf Abdullah, and M. Ibrahim, "A MATLAB/SIMULINK model to study the performance of the VFT for the interconnection of weak and strong AC grids," in *Proc. IEEE Int. Electr. Mach. Drives Conf. (IEMDC)*, May 2011, pp. 1635–1640.
[424] B. Bagen, D. Jacobson, G. Lane, and H. M. Turanli, "Evaluation of the performance of back-to-back HVDC converter and variable frequency transformer for power flow control in a weak interconnection," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2007, pp. 1–6.
[425] A. Abdel-Khalik, A. Elserougi, S. Ahmed, and A. Massoud, "Brushless doubly fed induction machine as a variable frequency transformer," in *Proc. IET Int. Conf. Power Electron., Mach. Drives (PEMD)*, Mar. 2012, pp. 1–6.
[426] R. Piwko, E. Larsen, and C. Wegner, "Variable frequency transformer—A new alternative for asynchronous power transfer," in *Proc. IEEE Power Eng. Soc. Inaugural Conf. Expo. Africa*, Jul. 2005, pp. 393–398.
[427] L. Wang and L.-Y. Chen, "Reduction of power fluctuations of a large-scale grid-connected offshore wind farm using a variable frequency transformer," *IEEE Trans. Sustain. Energy*, vol. 2, no. 3, pp. 226–234, Jul. 2011.
[428] L. Wang, S.-R. Jan, C.-N. Li, H.-W. Li, Y.-H. Huang, and Y.-T. Chen, "Analysis of an integrated offshore wind farm and seashore wave farm fed to a power grid through a variable frequency transformer," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–7.
[429] P. Marken, J. Roedel, D. Nadeau, D. Wallace, and H. Mongeau, "VFT maintenance and operating performance," in *Proc. IEEE Power Energy Soc. Gen. Meeting-Convers. Del. Electr. Energy 21st Century*, Jul. 2008, pp. 1–5.
[430] D. Nadeau, "A 100-MW variable frequency transformer (VFT) on the hydro-Québec TransÉnergie network–The behavior during disturbance," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2007, pp. 1–5.
[431] M. J. Asghar and Imdadullah, "A flexible asynchronous ac link (FASAL) system," Indian Patent 296 524, May 4, 2018.
[432] Imdadullah, M. Irshad, M. S. J. Asghar, and S. J. Arif, "Flexible asynchronous ac link for power system network interconnection," in *Proc. IEEE Energytech*, May 2012, pp. 1–6.
[433] Imdadullah, H. Rahman, and M. S. J. Asghar, "A flexible asynchronous AC link for two area power system networks," *IEEE Trans. Power Del.*, vol. 34, no. 5, pp. 2039–2049, Oct. 2019.
[434] I. A. Soliman, H. A. Abd el-Ghany, and A. M. Azmy, "A robust differential protection technique for single core delta-hexagonal phase-shifting transformers," *Int. J. Electr. Power Energy Syst.*, vol. 109, pp. 207–216, Jul. 2019.
[435] B. Chen, W. Fei, C. Tian, and J. Yuan, "Research on an improved hybrid unified power flow controller," *IEEE Trans. Ind. Appl.*, vol. 54, no. 6, pp. 5649–5660, Nov. 2018.
[436] Z. Tan, C. Zhang, and Q. Jiang, "Research on characteristics and power flow control strategy of rotary power flow controller," in *Proc. 5th Int. Youth Conf. Energy (IYCE)*, May 2015, pp. 1–8.

[437] D. Das, R. P. Kandula, J. A. Muñoz, D. Divan, R. G. Harley, and J. E. Schatz, "An integrated controllable network transformer–hybrid active filter system," *IEEE Trans. Ind. Appl.*, vol. 51, no. 2, pp. 1692–1701, Mar./Apr. 2015.

[438] K. Zhou, L. Huang, X. Luo, Z. Li, J. Li, G. Dai, and B. Zhang, "Characterization and performance evaluation of the superjunction RB-IGBT in matrix converter," *IEEE Trans. Power Electron.*, vol. 33, no. 4, pp. 3289–3301, Apr. 2018.

[439] B. B. Ambati and V. Khadkikar, "Variable frequency transformer configuration for decoupled active-reactive powers transfer control," *IEEE Trans. Energy Convers.*, vol. 31, no. 3, pp. 906–914, Sep. 2016.

[440] S. Mirsaeidi, X. Dong, D. Tzelepis, D. M. Said, A. Dysko, and C. Booth, "A predictive control strategy for mitigation of commutation failure in LCC-based HVDC systems," *IEEE Trans. Power Electron.*, vol. 34, no. 1, pp. 160–172, Jan. 2019.

[441] Y. Wang, W. Wen, C. Wang, H. Liu, X. Zhan, and X. Xiao, "Adaptive voltage droop method of multiterminal VSC-HVDC systems for DC voltage deviation and power sharing," *IEEE Trans. Power Del.*, vol. 34, no. 1, pp. 169–176, Feb. 2019.

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