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Voltage Sag Enhancement of Grid Connected Hybrid PV-Wind Power System Using Battery and SMES Based Dynamic Voltage Restorer

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ABSTRACT Renewable energy sources; which are abundant in nature and climate friendly are the only preferable choice of the world to provide green energy. The limitation of most renewable energy sources specifically wind and solar PV is its intermittent nature which are depend on wind speed and solar irradiance respectively and this leads to power fluctuations. To compensate and protect sensitive loads from being affected by the power distribution side fluctuations and faults, dynamic voltage restorer (DVR) is commonly used. This research work attempts to withstand and secure the effect of voltage fluctuation of grid connected hybrid PV-wind power system. To do so battery and super magnetic energy storage (SMES) based DVR is used as a compensating device in case of voltage sag condition. The compensation method used is a pre-sag compensation which locks the instantaneous real time three phase voltage magnitude and angle in normal condition at the point of common coupling (PCC) and stores independently so that during a disturbance it used for compensation. Symmetrical and asymmetrical voltage sags scenario are considered and compensation is carried out using Power System Computer Aided Design or Electro Magnetic Transient Design and Control (PSCAD/EMTDC) software.

INDEX TERMS Dynamic voltage restorer (DVR), energy storage, intermittent, power quality, voltage sag compensation.

I. INTRODUCTION

The energy demand of the world increased by 2.9% for the last year and that is almost double of the last ten years average energy demand which is 1.5% per year [1]. Based on the research study conducted by [2], the energy consumption forecast from 2018 to 2050 is done for industrial sub-sectors (energy intensive manufacturing, non-energy intensive manufacturing and non-manufacturing) and the result shows that energy intensive manufacturing industries energy consumption will increase by 50% compared to 2018. Due to its greenhouse gas emission problems, limited amount in its nature and instable price, non-renewable energy sources are not preferable to feed this energy demand. So that proper utilization of renewable energy sources (RES) such as wind and solar photo voltaic (PV) power should be the future plan to provide the energy consumption demands.

According to the 2050 energy transformation roadmap, renewable energies specifically wind and PV power sources will boost 2.5% of gross domestic product, increase employment rate, reduce 70% of CO_2 gas emissions and provide the energy demand with lowest cost [3], [4]. As RES are abundant, ecological, economical, and publicly acceptable compared to fossil fuel resources [5], the two-third of energy demand should be covered by RESs [3], [4], [6]. Due to its ecological impacts and correlated problems of non-renewable energy sources, countries want to harness their energy demand much on renewable energy sources [7]. This will be the realization of 2050 road map of international renewable energy agency as per the research works conducted [3], [4], [8]–[11].

Even though utilization of RESs are the bright future to shift from non-renewable energy sources, there should be optimal solutions to reduce end users' power fluctuation problems which arise from its intermittent nature [12]. The intermittent is mainly due to its dependency on weather conditions such as wind speed and solar irradiance

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[6], [9], [12], [13]. Due to the advancement of power electronics, nowadays most of industrial load types such as semiconductor manufacturing industries and chemical industries are sensitive to any power fluctuations [14], [15] and the power companies and customers should consider such cases to withstand any power fluctuation to be within the specified limit. This will be done using custom power devices (CPD) that will be connected either in series, shunt or a combination of the two at the sensitive load side and dynamic voltage restorer (DVR) is a series type CPD which is the most cost operational and comprehensive [14], [16]–[19].

A DVR is used to mitigate main power quality (PQ) problems that arise from voltage sag, swell, interruptions, harmonics and flickers which accounts more than 80% of PQ problems by protecting the critical consumer loads from tripping and consequent losses [16], [20], [21]. Among these, sag is the most frequent voltage disturbance which is typically caused by a fault at the remote bus, switching of heavy loads, starting of large motors and transformer energizing. This is accompanied by a phase angle jump [19]. In case of PV-wind power system, sag could be happening due to sources intermittent in addition to the above mentioned causes.

The energy source of the DVR can be directly from the main source without storage element [16], [17], [22], using self-storage capacitors and using external storage devices such as battery energy storage (BES) and super magnetic energy storage (SMES) [18], [23]–[25]. The DVR is used for power quality improvement of wind power system [16], for PV system [26], for conventional power system [17], [18] and for PV-wind hybrid system [27]. Considering the storage cases and fast response ability, a DVR is used to enhance power quality problems in combination with SMES [24], [28], with a combination of BES and SMES for conventional power system [18], [29].

If the energy source of the DVR is from the main source, the DVR will be incapable to perform well during a deep sag condition. In the other case also, if the DVR has its own energy storage among the one from BES or SMES, the performance is not well. This is due to the high power, low capacity and medium power, high capacity characteristics of SMES and BES devices respectively [21], [28]. That means if only SMES is used alone as energy storage, the DVR performance promptly, but for a short period of time and if only BES is used, the response time will be slow even though it performs for elongated time. Thus, in order to increase the performance capacity of the DVR, BES and SMES units should be integrated [18], [29]. The theoretical research and device development of BES - SMES hybrid energy storages (HES) based DVR is in a good pathway, and its operation in the micro grid PV-wind power systems are viable research area.

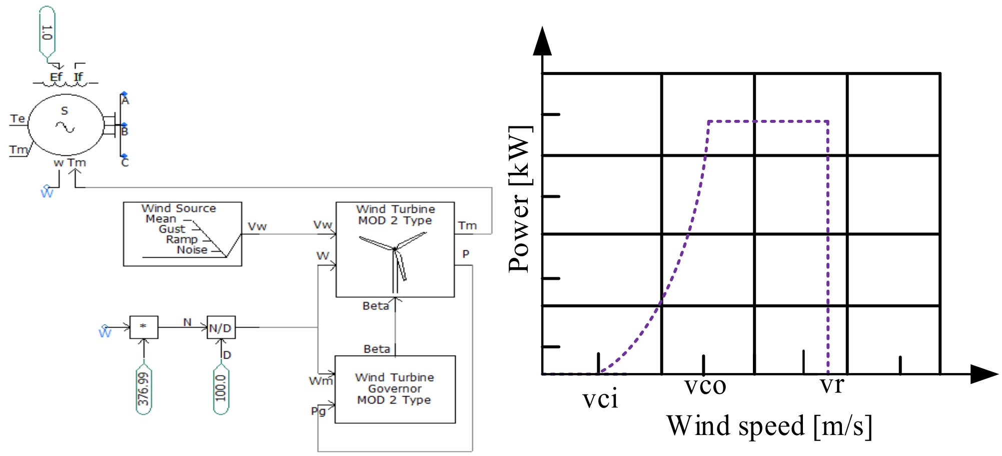
A detailed DVR topologies, control and compensation strategies are presented in [19]. The compensation strategies mainly focus to minimize DVR injection transformer ratings (in-phase compensation) and the DC link capacitor storage capacity (energy optimized compensation) [18], [19] and these strategies may lead to premature tripping out of the sensitive loads due to its incapability to correct phase jumps. Phase jump correction is the capability of pre-sag compensation strategy since it locks instantaneous magnitude and phase angle of the line voltage [18], [28]. So by considering the optimal sizing of injection transformer and DC link capacitor storage capacity pre-sag compensation is broadly preferable.

PV and wind power systems are not stable and cannot supply firm electrical output. In this study, a detail and comprehensive emphasis are given for the HES based DVR system to play a vital role in order to utilize renewable energy sources effectively as a micro grid system and to supply an improved power to the connected sensitive load. The voltage fluctuation enhancement of grid connected PV-wind hybrid power system is simulated. The fluctuation consideration is mainly due to the non-stable power output of renewable energies (wind and PV sources) and fault conditions. The compensation strategy used in this research is a pre-sag compensation and it is presented in detail with its control and working principal. The performance of the proposed method is validated using PSCAD simulation. Features of wind and PV power systems are discussed in section 2. The proposed BES-SMES HES based DVR is presented in section 3 and principle and control strategy of voltage source convertor (VSC) discussed in section 4. Simulation results and conclusion presented in section 5 and 6.

II. GRID CONNECTED HYBRID PV-WIND POWER SYSTEM AND ITS FEATURES

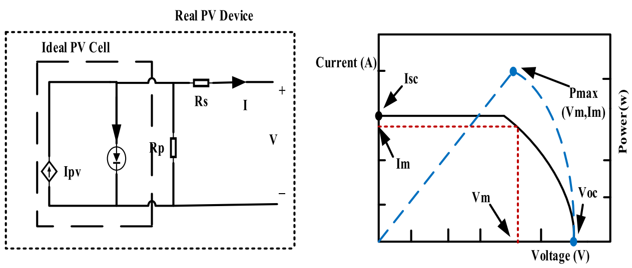
Solar and wind energy sources are a promising electrical energy sources due to its abundant nature and gradually declining investment costs [3], [4], [30]. The global installed capacity of wind and solar PV energy sources are more than 539 GW [31] and 405 GW [32] by 2017 respectively. Wind and PV energy sources are weather dependent which are mainly affected by wind speed and solar irradiance [5], [16], [31], [32]. The power output of wind turbine (P_{WT}) can be calculated using wind speed data and power curves prepared by wind turbine companies as shown in Fig. 1 and (1) [5], [31], [33]. The output power is non-linear and non-zero in the interval of cut-in and rated wind speed values. In that case, the power produced is not constant and it may be under the demand power so that it should be combined with another source of energy for sustained power delivery to end-users.

The power output of PV cells is calculated based on the I-V characteristics of the cell as shown and Fig. 2 and TABLE 1 [5], [34], [35]. V_{oc} and I_{sc} are mainly depends on solar irradiance and temperature of the PV cells as described in (3) and (4) [5], [35]. Due to this, standalone PV power plants which produced fluctuated power are not desirable specifically for sensitive loads which demand uninterrupted and sustained power supply. As a general case, the PV cell maximum power can be calculated as (5) and the cell temperature estimation



(a) Wind turbine system (b) Power curve of wind turbine

FIGURE 1. **Wind turbine system and its power curve.**



(a) Equivalent electric circuit of PV cell (b) PV cell power curve

FIGURE 2. **PV cell power circuit and curve.**

can be done as of (6) [30], [35], [36].

$$P_{WT}(v) = \begin{cases} 0, & 0 < v < v_{ci} \\ 0.5\rho A v^3 C_p, & v_{ci} \le v < v_r \\ 0.5\rho A v_r^3 C_p, & v_r \le v < v_{co} \\ 0, & v \ge v_{co} \end{cases} \quad (1)$$

where ρ, A, $C_p v_r$, v_{ci} and v_{co} are the air density, swept area, power coefficient, rated wind speed, cut-in wind speed and cut-out wind speed values respectively.

$$P_{max} = V_{oc} I_{sc} FF \quad (2)$$

where P_{max}, V_{oc}, I_{sc} are the maximum output power, the open circuit voltage and short circuit current of the PV cells and FF is the fill factor.

$$V_{oc} = V_{oc}^{*} + \beta_v (T - 25) \quad (3)$$

where V_{oc}^{*}, β_v and T are the open circuit voltage of the PV cell under standard test conditions, the temperature coefficient of PV cells referent to the open circuit voltage and the cell temperature respectively.

$$I_{sc} = \frac{G}{G_N}\left(I_{sc}^{*} + \beta_i (T - 25)\right) \quad (4)$$

where G and G_N are the incident solar irradiance and the incident solar irradiance under standard test conditions respectively. I_{sc}^{*} and β_i are the PV cell's short circuit current under standard test conditions and the temperature coefficient of PV cells referent to the short circuit current respectively.

$$P_{pv} = P_{STC} \frac{G}{G_n}\left(1 - \gamma (T - 25)\right) \quad (5)$$

where P_{STC} and γ are the PV cells maximum power under standard test conditions and maximum power temperature coefficient.

$$T = T_{amb} + \frac{G}{G_{NOCT}}\left(T_{c,NOCT} - T_{NOCT}\right) \quad (6)$$

where T_{amb}, G_{NOCT}, $T_{c,NOCT}$ and T_{NOCT} are the environmental temperature, incident solar irradiance at nominal operating cell temperature, the nominal operating cell temperature provided by the manufacturer and nominal operating cell temperature.

To deliver a steady power to the customers from wind and PV power plants, enhancing of fluctuations that elevated by intermittent is needed. The on grid and off grid hybrid renewable system are preferable, and reliable to optimize the impact of intermittent [5], [35]. For economic feasibility also hybrid power systems are desirable and on grid and off grid hybrid PV-wind power systems are installed in different countries across the world and this is mainly desirable in those countries having more islands [5], [15], [34], [35]. The mini grid system can accommodate different renewable energy sources alone or different renewable energy sources and operated with the main grid line [5], [37], [38].

In this study, on grid hybrid system is demonstrated as shown in the Fig. 3 which accommodates solar PV, wind and main grid low voltage line connected at the PCC bus which provides power to the sensitive load. During normal conditions, the solar PV, wind system and main grid line supply a constant 5 kV to the PCC bus. In case of abnormal conditions due to the intermittent, PV and wind power systems will supply under or above 5 kV to the PCC bus. In this condition installation of appropriate CPD is the main focus to withstand fluctuation conditions from being affected the sensitive load.

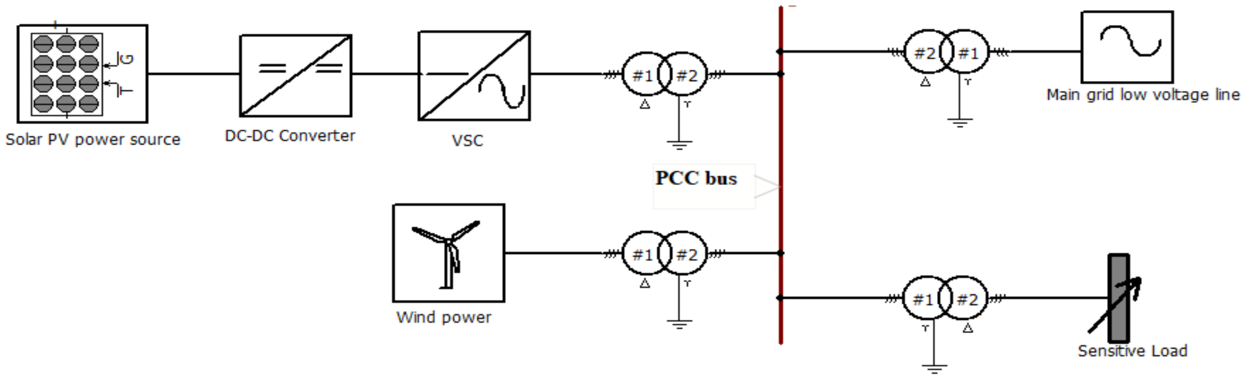


FIGURE 3. On grid PV-wind hybrid system.

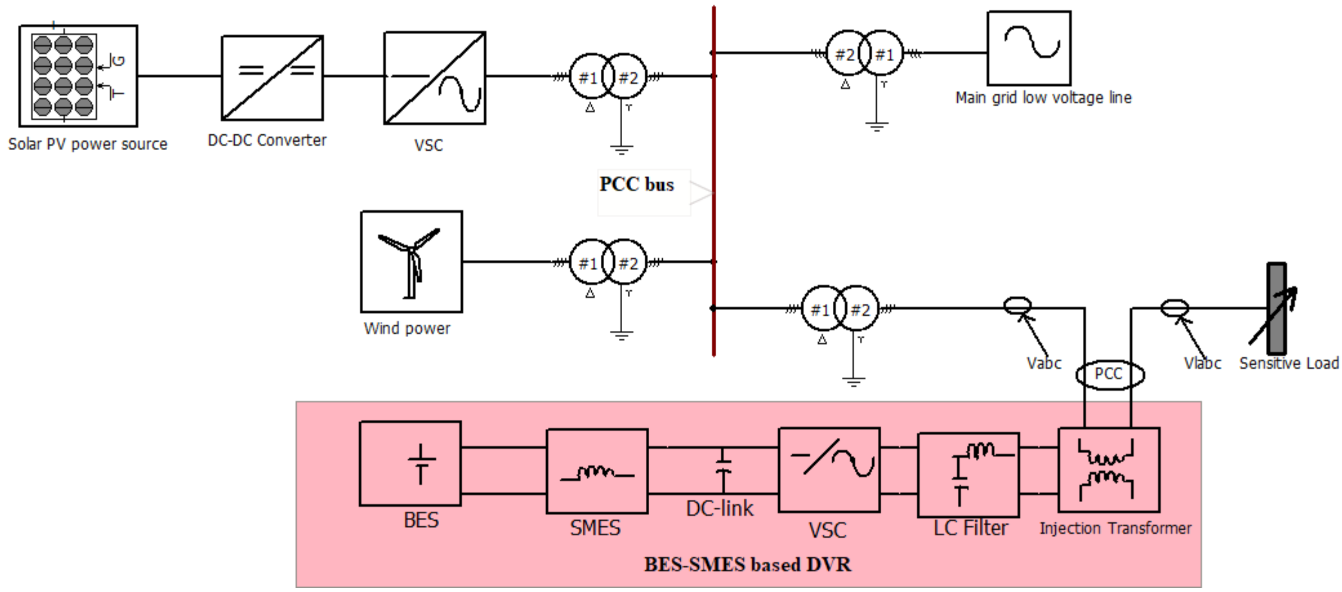


FIGURE 4. The proposed BES-SMES based DVR for on grid PV-wind hybrid system.

III. BES-SMES HES BASED DVR

Electrical energy in an AC system cannot be stored electrically. However, energy can be stored by converting the AC electricity and storing it like electromagnetically using SMES and electrochemically using BES. Integration of these energy storage technologies with CPD for sensitive loads is one of the possible applications for power quality improvement [25]. SMES device is used to store electric energy in its superconducting coil without resistive lose during voltage swell scenarios in the system [18], [39] and release the stored energy during voltage sag to maintain the load voltage stable [40]. When the superconducting coil operated with very high current, it becomes an inductive load when it is charged and it served as decreasing current source while it is discharged [18], [40]. SMES device is characterized by its large power density and prompt response time while BES have large energy density and capable to release its stored energy for prolonged time [21], [28]. For sensitive loads, a combination of BES and SMES devices is effective for fast response and somewhat elongated time is needed to withstand any fluctuation from being affected sensitive loads [18], [41].

Fig. 4 and Fig. 5 shows the overall and detailed block diagram of a BES-SMES based DVR which is operated to enhance any voltage fluctuations for on grid PV-wind hybrid power system as mentioned in Fig. 3 and with its parameters as mention in Table 1. The BES-SMES based DVR which connected on the sensitive load side of distribution line, consists of injection transformer, LC filter, a bidirectional VSC, a DC-link capacitor, a SMES device and BES with its respective equipped choppers.

Disturbance detection and determining the reference signal that used for voltage injection are the basic parts of DVR control system [42]. The voltage sag/swell detection is done by measuring the three phase line instantaneous real time voltage at the point of common coupling (PCC) and analyze it using the root mean square per unit voltage (V_{pu}) measurement so that the voltage disturbance can be recognized. The determination of reference signal generation is related to the type of the compensation method used among the

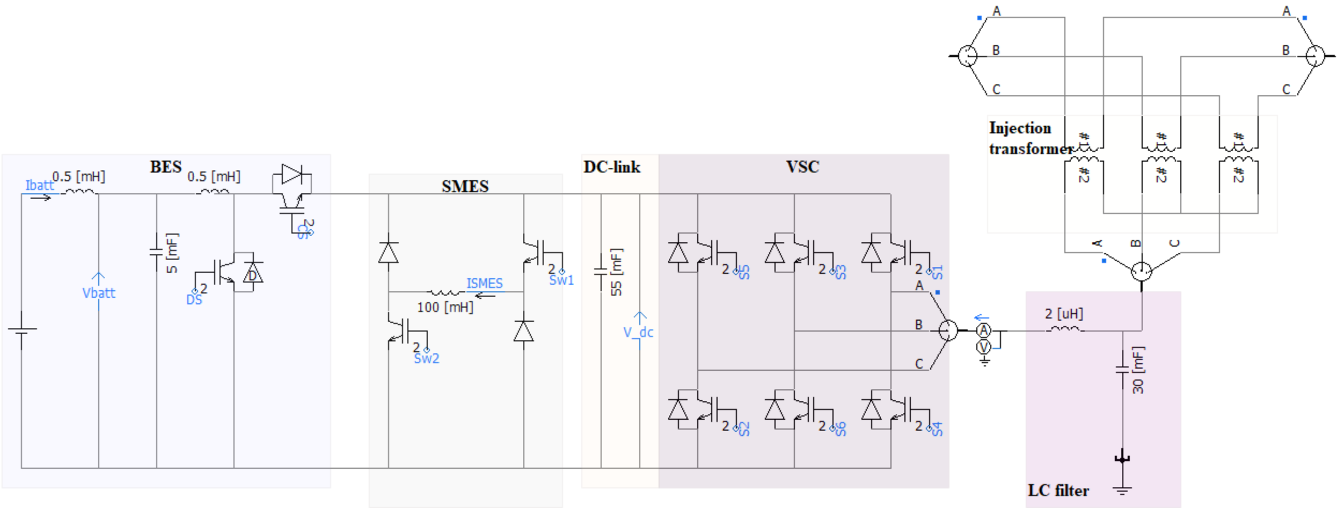


FIGURE 5. BES-SMES based DVR detail block diagram.

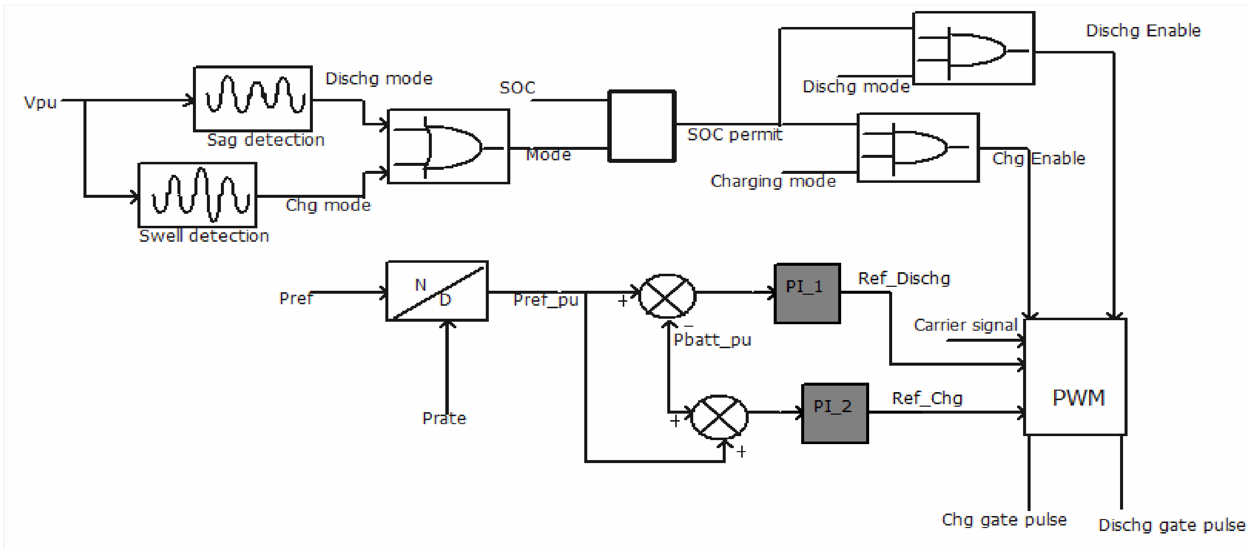


FIGURE 6. Control block diagram of BES.

TABLE 1. Specifications of the on grid PV-wind hybrid system.

Parameters	value
PV source voltage step up transformer	1 kV/5 kV, 60 Hz
Grid line voltage and step down transformer	11 kV/5 kV, 60 Hz
PCC Bus base voltage	5 kV
Distribution transformer	5 kV/0.48 kV, 60 Hz
Sensitive load capacity	0.1 MW + 0.1 MVAr

well-known compensation methods such as in-phase, pre-sag, energy minimized and hybrid compensation methods. When Vpu at the PCC is under the normal value (voltage sag condition), the DVR will inject and compensate the missing voltage using the HES devices and during over V_{pu} value (voltage swell condition), the DVR will absorb the excess voltage to be stored in its HES so that the load voltage will be constant and within the standard value. In these two cases the DVR operation will be done through a proper controlling of BES, SMES and the VSC as shown in the Fig. 6, Fig. 7, Fig. 9 and based on the parameters presented in Table 2.

As shown in Fig. 5, by observing the voltage level at the PCC and SOC of the battery, the battery will charge, discharge or stayed in energy storing states. The SOC of the battery is measured by comparing its actual capacity with its nominal capacity. The BES will be charged and discharged when the insulated gate bipolar transistors (IGBTs) switches named as charging switch (CS) and discharging switch (DS) ON respectively. In order to protect the battery from being damaged due to over charged and discharged, its state of charge (SOC) is considered to be within the interval of 5% to 100% in addition to the charging and discharging mode conditions. This will be done by the signal called SOC permit which does not permit charging and discharging when the

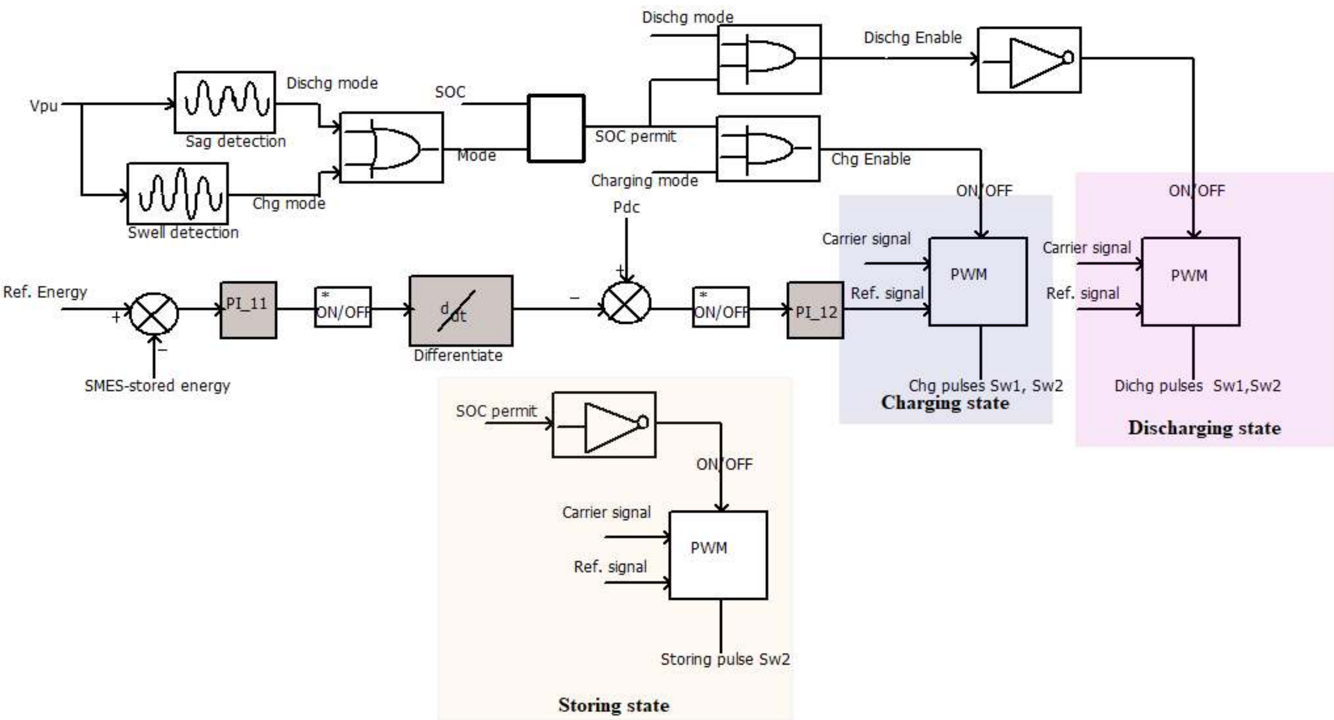


FIGURE 7. Control block diagram of SMES.

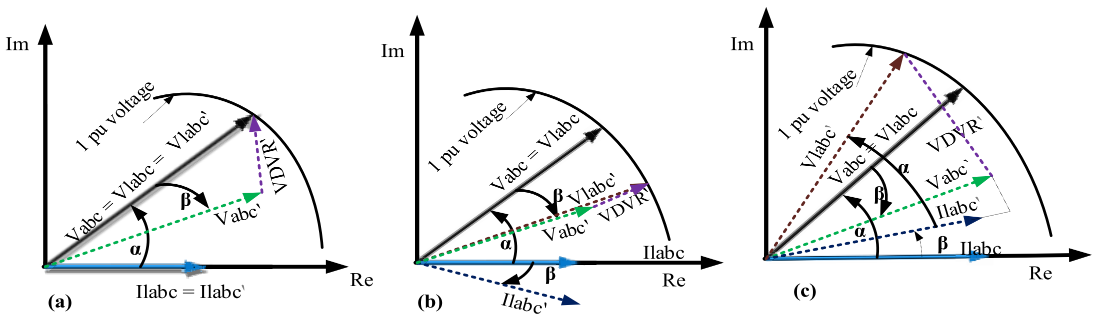


FIGURE 8. Voltage compensation strategies of DVR (a) pre-sag compensation, (b) in phase compensation, (c) energy optimized compensation.

SOC is 100% and 5% respectively. If the SOC is at the minimum threshold only charging is permitted and if SOC is equal to maximum threshold only discharging is permitted. Whereas, if SOC value is within the given interval, based on the sag or swell detection the battery will charge or discharge as described in the Fig. 6. CS and DS will be ON if and only if the charge enable and discharge enable values are one respectively which depends on the SOC permit and mode. Based on the rating of the battery, the reference power is selected to get per unit value and by comparing it with the battery per unit value, the error will transferred to the proportional integral (PI_1) controller to generate the discharging reference signal (Ref_Dischg). To generate the charging reference signal (Ref_Chg), the reference power per unit value will be summed up with the battery power per unit and transferred through PI_2. By comparing these reference signals with the carrier signal which have 5 kHz, charging gate pulses and discharging gate pulses will be generated. The BES will be at idle (storing state), if the voltage level at the PCC is normal or even though sag or swell happen, but SOC is 5% or 100% respectively.

As it is shown in Fig. 5 and Fig. 7, by observing the voltage level at the PCC and SOC of the SMES, the SMES will charge, discharge or stayed with energy storing states. To charge the SMES, both switches Sw1 and Sw2 should be turned on and to discharge both Sw1 and Sw2 should be turned off. In the energy storing state, Sw1 will be turned off and Sw2 will be turned on.

The reference energy compares with the stored energy in the SMES, supply it to PI_11 and by multiplying with ON-OFF value it will be transferred through the differentiator to produce the power. After that, the power from SMES will be compared with the DC power (Pdc) from the DC-link capacitor and multiply with ON-OFF value so that finally

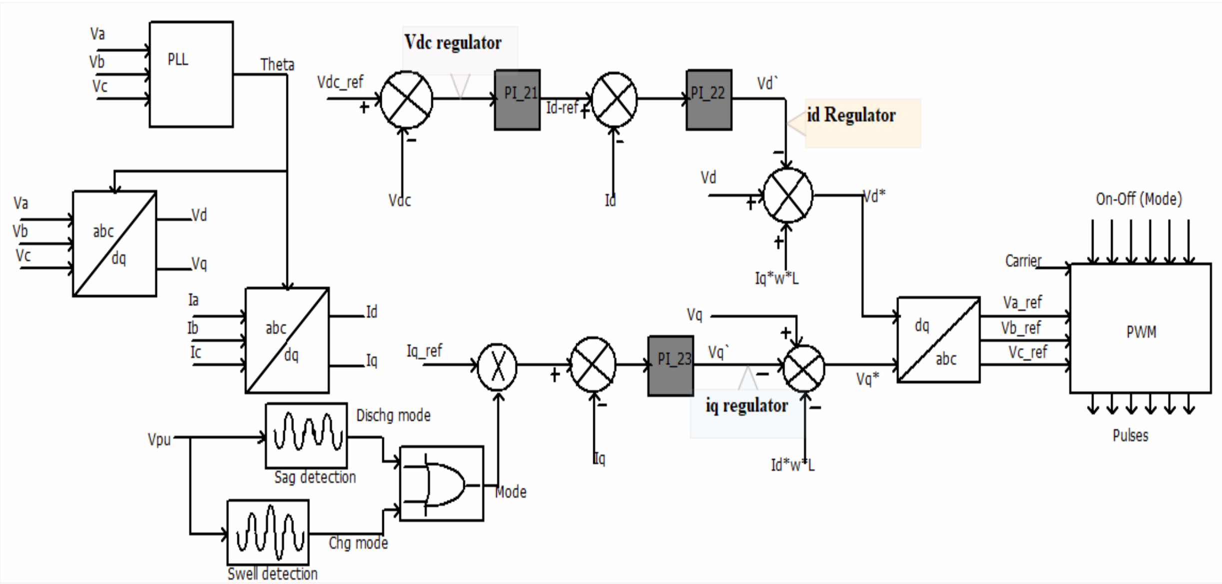


FIGURE 9. Control block diagram of VSC.

TABLE 2. Specifications of BES-SMES HES based DVR.

Parameters	value
Filter inductance	2 µH
Filter capacitance	30 mF
DC-link capacitance	55 mF
Dc-link rated voltage	500 V
SMES inductance	0.1 H
SMES critical current	150 A
BES capacity	200 Ah
Battery nominal voltage	600 V
Injection transformer rating	0.48 kV/0.48 kV, 60 Hz

transferred to PI_12 to generate the reference signal. Like the BES, the SMES will charge and discharge if its' SOC is below 100% and above 5% respectively. The SOC of the SMES is measured by comparing its actual energy stored with its maximum energy capacity. When the SOC is in between 5% and 100%, and if voltage swell or sag happen at the PCC, the SMES will be on charging or discharging state respectively. Otherwise, if the voltage level at the PCC is normal or it is at swell condition, but SOC of the SMES is 100%, or it is in sag condition, but SOC of the SMES is 5% then the SMES will be at energy storing state.

Based on the status of the BES and SMES devices, the overall BES-SMES based DVR will operate in these three states.

IV. PRINCIPLE AND CONTROL STRATEGY OF VSC

Different voltage compensation strategies such as pre-sag compensation, in-phase compensation and energy optimized compensation of the VSC of DVR are presented [18], [19], [33].

The pre-sag compensation strategy which is also used for this research work, is based on the restoration of the sagged and swelled voltage magnitude and phase angle to its healthy state. It injects active power during sag conditions and reactive power during swell conditions. This is done by taking the real time voltage magnitude and phase angle of the three phase line voltages before any voltage disturbance to be locked and stored independently so that in case of disturbance it used to compensate properly [18], [19]. The main advantage of pre-sag compensation compared to in-phase and energy optimized compensation is its capability to compensate phase jumps even though it needs some additional active power from the DC-link [18], [19], [33]. Phase jump should get a strong consideration since it is a critical issue for sensitive loads which produces transient and circulating current. These compensation strategies are clearly shown in Fig. 8. Vabc and Vabc' are the three line phase voltage at the PCC before disturbance and during disturbance respectively. Vlabc, Vlabc' and VDVR' are the three line phase load voltage before disturbance, during disturbance and injected voltage by the DVR during the disturbance. Similarly Ilabc and Ilabc' are the three line phase currents at the load before any disturbance and during a disturbance respectively.

The pulse width modulation (PWM) converter is current regulated with direct axis current (id) used to regulate the DC-link voltage and the quadrature axis current (iq) component used to regulate the reactive power [43].

In this study a sinusoidal pulse-width modulation (SPWM) switching technique and vector control strategy is used in which the AC current of the VSC (Iabc) is controlled to adjust active and reactive power exchange between the AC and DC sides of VSC as shown in Fig. 5 with detail control strategy in Fig. 9.

Iabc is decomposed into id and iq components by applying the Park transform, which are in-phase with, and perpendicular to the AC phase voltage *Vabc* respectively. The direct

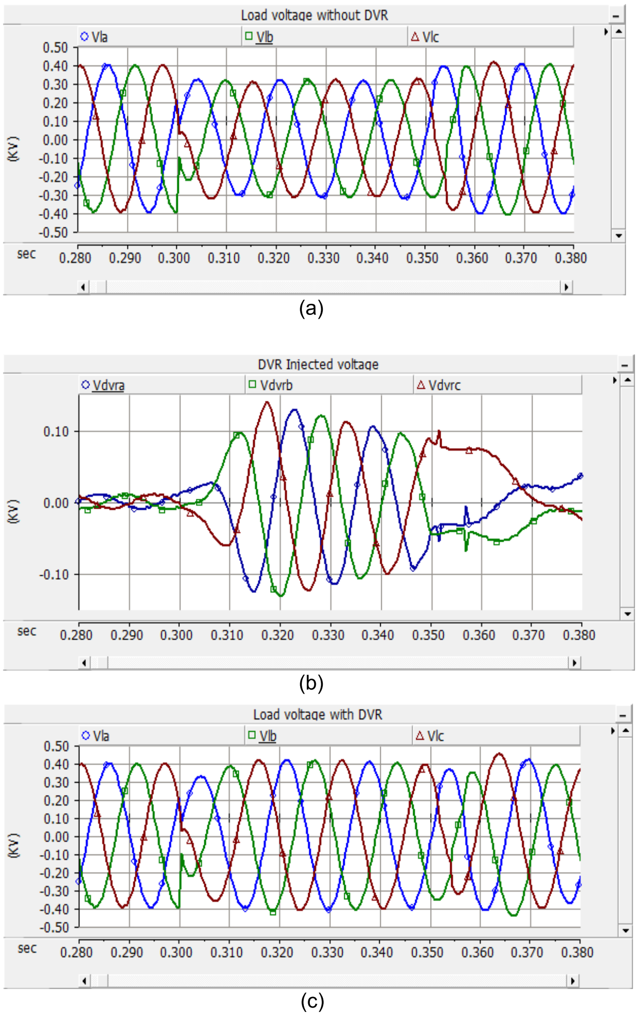


FIGURE 10. Simulation results and DVR response for 25% symmetrical voltage sag case (a) load voltage without DVR, (b) DVR injected voltage and (c) load voltage with DVR.

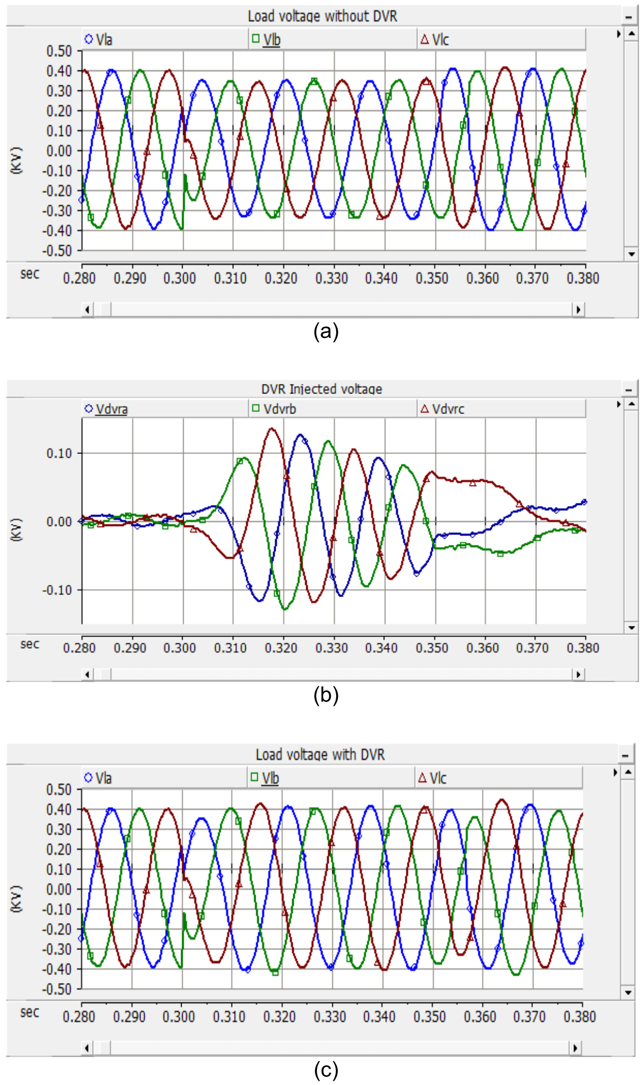


FIGURE 11. Simulation results and DVR response for 12% symmetrical voltage sag case (a) load voltage without DVR, (b) DVR injected voltage and (c) load voltage with DVR.

component regulates the active power transfer between the AC and DC sides of VSC so that the dc-link voltage will be adjusted by controlling *id*. In the other way, controlling of *iq* regulates the reactive power level at the AC terminals of the VSC. The reference phase angle of Iabc decomposition is taken from the real time three phase voltage (Vabc) using a phase-locked loop (PLL) as described in Fig. 9. Vabc is taken and locked during normal condition using PLL and stored independently so that during any disturbance it used to compensate based on reactive power theory and current control method.

As it is seen in Fig. 9, there are three regulators (Vdc regulator, id regulator and iq regulator) which have its own input parameters and PI controllers. The regulators combination used to provide the set points vd∗ and vq∗ which used to obtain the modulation waveforms Va_ref, Vb_ref and Vc_ref by applying Inverse Park Transform to vd∗ and vq∗. Finally PWM switching pulses are produced by comparing the modulation waveforms with a triangular carrier signal which have carrier frequency value of 5040 Hz, through the six interpolated firing pulse blocks. On-OFF of the interpolated firing pulses is done using the respective phases V_{pu} values so that it will be ON if and only if a voltage sag or swell happened and otherwise it will be OFF.

V. SIMULATION RESULTS AND DISCUSSIONS

To test the performance of the proposed BES-SMES based DVR system for PV-wind hybrid energy sources as shown in Fig. 4 with its parameters described in Table 2, simulation is carried out using PSCAD/ EMTDC. For this simulation test, a fault is applied at the PCC bus for 50 millisecond time duration for symmetrical and asymmetrical conditions which produce symmetrical and asymmetrical voltage sags.

As it is presented in Fig. 10 (a) and Fig. 11 (a), the load voltage was dropped to 75% and 88% of its nominal value respectively. By using BES-SMES based DVR, the voltage sag was improved to normal as shown in Fig. 10 (c) and Fig. 11 (c).

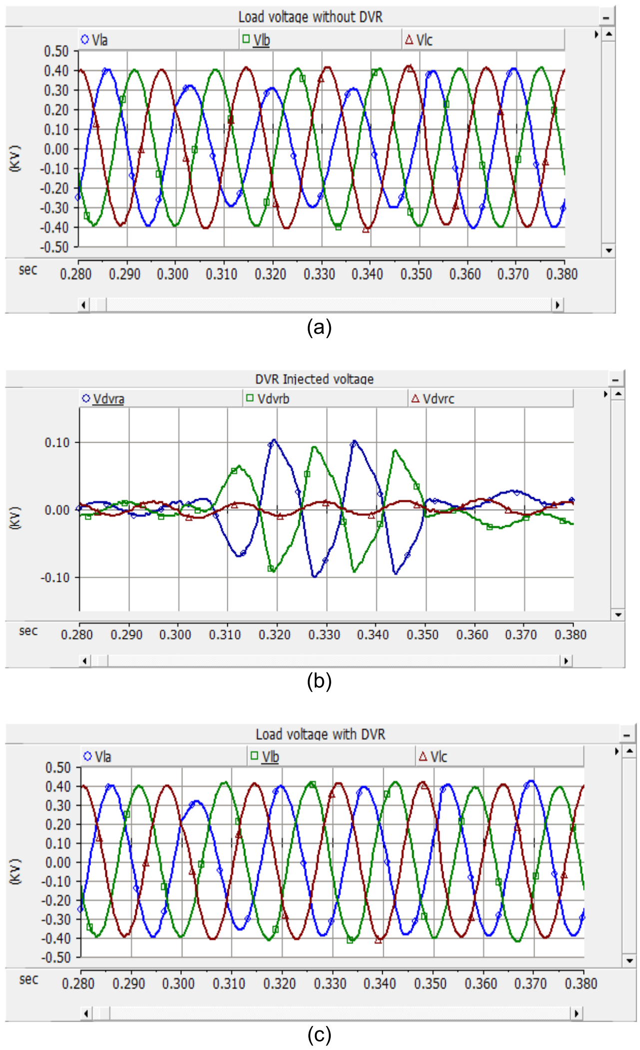


FIGURE 12. **Simulation results and DVR response for 25% asymmetrical voltage sag case (a) load voltage without DVR, (b) DVR injected voltage and (c) load voltage with DVR.**

In similar way, Fig. 12 (a) and Fig. 13 (a) depicted a single line voltage sag of 25% and 35% from its nominal value respectively. In addition to this, phase shift also happened, including other phase. Whereas, the HES based DVR compensated the missing voltage appropriately as described in Fig. 12 (c) and Fig. 13 (c). Due to the switching cases at the start and stop of operation time of the DVR, for a very short moment the compensation is not complete as shown in the compensation simulation results.

In real cases, the symmetrical and asymmetrical voltage sags could happen not only due to a fault, but also due to the source fluctuation in the PV-wind power systems. Based on its' intermittent nature of the source, both PV and wind power system could produce symmetrical sag and if separate PV systems connected to the individual phases, asymmetrical voltage sag also will be produced. Whatever, the proposed BES-SMES based DVR will compensate the sag voltage whether it happened due to a fault or source intermittent.

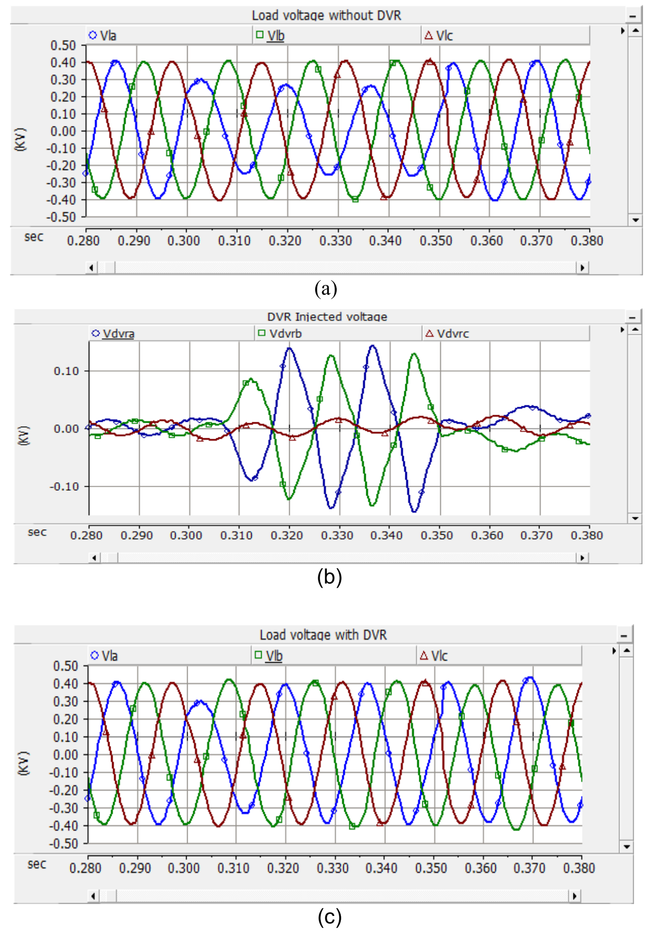


FIGURE 13. **Simulation results and DVR response for 35% asymmetrical voltage sag case (a) load voltage without DVR, (b) DVR injected voltage and (c) load voltage with DVR.**

VI. CONCLUSION

In this paper, a voltage sag enhancement of sensitive load which gets power from grid connected PV-wind power system is demonstrated using HES based DVR. The proposed DVR targets to protect the sensitive load from being affected by any voltage fluctuation which arise either from fault condition or unstable power output of PV-wind system. The control and operations of BES and SMES devices is developed by observing voltage condition of the grid at the PCC and the SOC levels of battery and SMES. In addition to this, for full realization of the proposed DVR system the control and operation of the VSC is developed by observing the voltage level at the PCC. The pre-sag compensation strategy is selected based on the capability of both magnitude and phase jump restoration. Based on the conditions, three operating states of the HES based DVR are defined, which are normal (idle state), charging state and discharging state. The effectiveness of the proposed operating states has been demonstrated in realistic cases. In the simulation, different voltage sag depth scenarios are considered for both symmetrical and asymmetrical voltage imbalances and the HES based DVR works well. A combination of voltage sag, voltage swell and harmonics scenarios will be demonstrated in the future works.

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