CAPACITOR COMMUTATED CONVERTERS FOR HIGH POWER HVDC TRANSMISSION

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Abstract
Two concepts for the transmission with a high power capacity using HVDC technology are analysed in this paper. The technology of Capacitor Commutated Converters (CCC) is presented and the design of two system models is described. Their steady-state as well as transient performance is presented and the CCC is compared to the conventional HVDC transmission. The advantages of the CCC for high power transmission are shown.

Keywords: East-West interconnection, HVDC transmission, CCC, capacitor commutated converter, transient stability

I. INTRODUCTION

After the connection of the CENTREL to the UCTE power system and due to political approach of the countries in Eastern Europe towards the European Union, their power grids are in a process of new orientation. There is an effort of using the advantages of an electrical interconnection between the UCTE and the Russian power system.

A benefit of a high power East-West interconnection over the long distance from Germany to Russia of about 1000 km is the exchange of peak load due to the time shift. This results in the compensation of load peaks in the load curve profile of the networks. Moreover the grids can support each other with reserve power during faults and outages. In this way both systems can reduce their installed power capacities and there is a possibility of utilising the power plants more efficiently [1].

The maximum capacity level for the transmission depends on the available capacity on transmission lines and, in the case of total loss of the interconnection, the transient stability must be ensured. Consequently the maximum rated capacity of the transmission system is determined to be 4000 MW [1].

Since there are big differences in power system management and control a synchronous connection between the Eastern and Western networks can currently not be realised. So the only way of transmitting a large quantities of electrical power over long distances is the High-Voltage Direct-Current (HVDC) transmission. In the case of a later synchronous interconnection between the power networks, the HVDC system could support the power exchange further on and the stability of combined network can be improved [2].

The point of interconnection in Eastern Europe can be a problem for the transmission system. If the short circuit ratio (SCR) of the network is low, the operation of a HVDC converter can be difficult due to its consumption of reactive power.

A few years ago a new concept for HVDC systems was presented [3]. The Capacitor Commutated Converter (CCC) has capacitors connected in series between converter transformers and valves as shown in Fig. 1. These commutation capacitors (CC) provide an additional commutation voltage allowing to operate the rectifier at smaller firing angles respectively the inverter at smaller extinction angles [3, 4, 5].

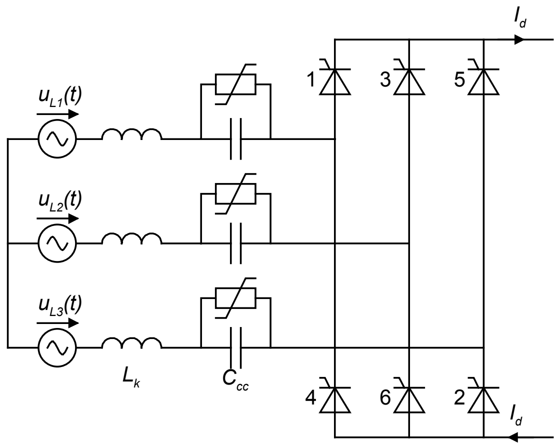


Fig. 1: Capacitor Commutated Converter (CCC)

Hence the consumption of reactive power and thus the size of the filter capacitance is well reduced. In this way the steady-state and the transient stability of the system is increased. The CCC can be operated at networks with lower SCR than the HVDC converter, which is shown in this paper.

II. SYSTEM MODELLING

Using the conventional and the CCC-HVDC technology, design and modelling of a transmission system with a rated power capacity of 4000 MW over a distance of 1000 km is described in this chapter. The model should meet steady-state behaviour as well as the transient performance of both systems. With these models transient simulations are performed to analyse and compare their response to transient system faults. The simulation runs are realised using the transient simulation program EMTDC / PSCAD.

II.1. BASIC SYSTEM CHARACTERISTICS

The maximum transmission capacity of the HVDC network is limited to 4000 MW due to the stability of the ac networks. To realise the dc transmission at this power level, the HVDC converter is designed as a bipolar system with a ground electrode. The rated dc voltage is ±600 kV, hence the rated dc current is I_{dr} = 3.33 kA.

The rectifier is operated in constant dc power control mode, whereas the inverter is controlled to a given minimum extinction angle γ_{min}. In the control of the converter VDCOL is included enhancing the stability of the system at transient ac voltage drops [6]. The design of control for the conventional as well as the CCC converters is basically the same, modelled on the control of the CIGRE benchmark model [7].

In Fig. 2 a schematic diagram of the whole system is shown. An ac network, a power plant and the reactive power compensation, i.e. ac filters and capacitors, are connected to the busbar at the rectifier side. The ac network is a relatively strong system with a SCR of 5. The generator supports a part of the power transmitted. The rated power output is controlled a constant value of 2600 MW and the generator bus voltage is controlled to be constant.

At the inverter side only the ac filters and compensation capacitors for supplying reactive power and the ac system are connected to the inverter bus. The short circuit ratio of this network is of special interest. It is assumed to be a high-impedance ac network. So the SCR is changed during the analysis of the systems.

II.2. CONVENTIONAL HVDC SYSTEM

The main converter parameters are specified in Table I. The ratings of the converter transformer can be seen as well as the minimum extinction angle γ_{min} and the installed reactive power Q_c at each converter bus. To filter the harmonics produced by the converter two ac filters for the 13th, for 11th harmonic and a high pass filter are installed. Each is designed to supply 500Mvar of reactive power at rated frequency.

TABLE 1 - Converter parameters

	γ_{min} °	Q_c Mvar	S_{rT} MVA	U_{rT} kV / kV	u_{kr} %
HVDC	18	2500	1212	400/257	18
CCC	2	850	1075	400/233	18

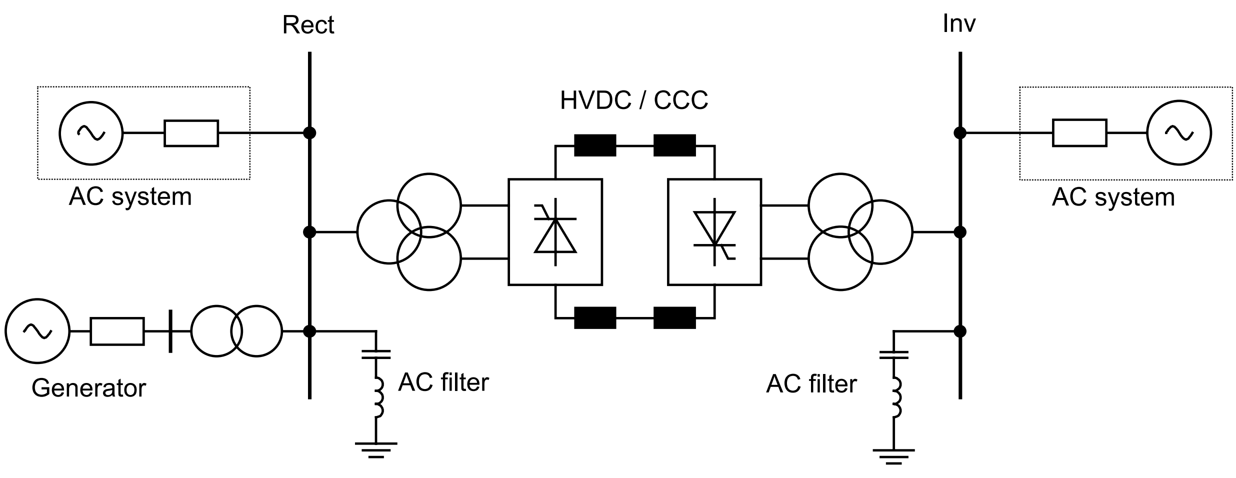


Fig. 2: Model system

II.3. CCC SYSTEM

In contrast to the conventional HVDC transmission system the reduced extinction angle, due to the additional commutation voltage supported by the CCs, leads to a decreased consumption of reactive power. So the ac filter capacitors can be smaller and the quality of the filters can be improved.

It is practical to limit the size of the capacitors to a value allowing to extend the firing angle range at the inverter up to 180° [5]. The capacitance of the CCs used in this model is determined to C_{cc} = 141,5 μF.

Fig. 3 shows the single line circuit diagram for the CCC inverter. The main parameters are also displayed in Table I. The values for the rated dc voltage and current are equal to the design of the conventional HVDC. The inverter bus voltage is 400 kV at the nominal operation point.

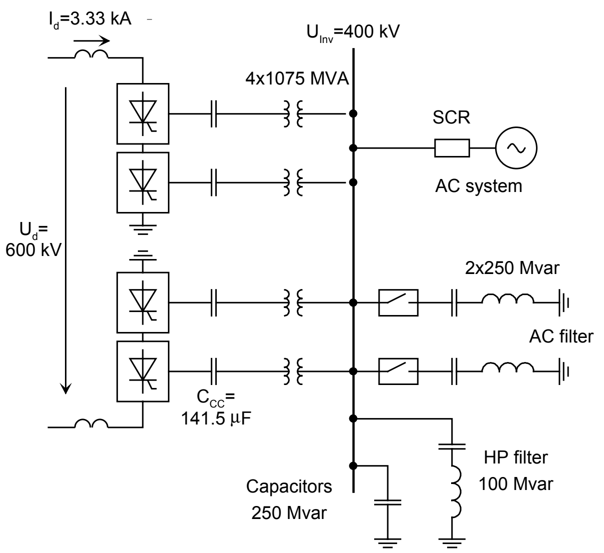


Fig. 3: Inverter station of the Capacitor Commutated Converter

Compared to the conventional converter design the rated secondary transformer voltage can be smaller and the rated power of the transformer can be reduced as well. For the 11th and 13th harmonics ac filters with 250 Mvar are installed. The high pass filter supplies 100 Mvar at nominal ac bus voltage. Additionally a capacitor bank with 250 Mvar is connected to the busbar. Therefore the filters can be installed in only one unit. The total installed reactive power Q_c is 850 Mvar, this is about 21 % of P_{rd}.

A disadvantage of the CCC concept is the increase in high ac harmonic currents caused by a reduced commutation time and thus a reduced overlap angle [3]. This effect can be met by increasing the quality of the ac filters. Improving the quality is possible since the filter capacitance is reduced by the factor of 2.

III. STEADY-STATE PERFORMANCE

In this chapter the steady-state performance of both HVDC systems is described and compared using MAP.

III.1. REACTIVE POWER CONSUMPTION

The largest advantage of the CCC is the reduced consumption of reactive power. Hence smaller ac filter capacitors can be installed. During small load operation the filters don't have to be switched.

Fig. 4 a. and b. show the reactive power consumption of the conventional converter and the CCC as a function of the dc current referred to the rated dc power P_{rd}.

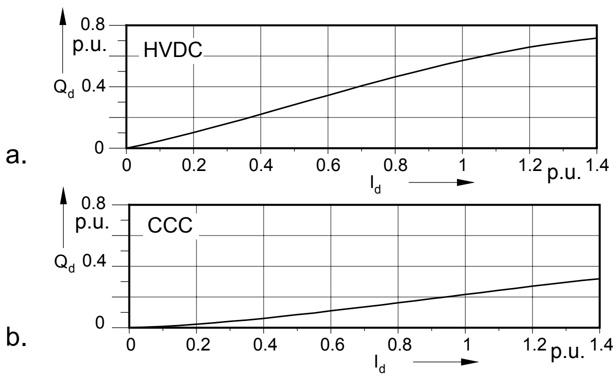


Fig. 4: Reactive power curves of conventional HVDC (a.) and CCC (b.)

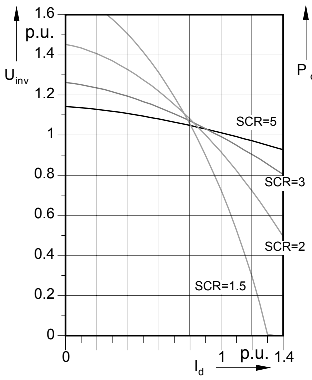
The CCC consumes a reactive power of 0.23 P_{rd} at nominal operation point, whereas the conventional HVDC requires about 60 % of P_{rd} when operated at an ac network with a short circuit ratio of 3. Hence, at nominal operation point the reactive power consumption is reduced by nearly 2/3rd of its former value.

III.2. MAXIMUM AVAILABLE POWER (MAP)

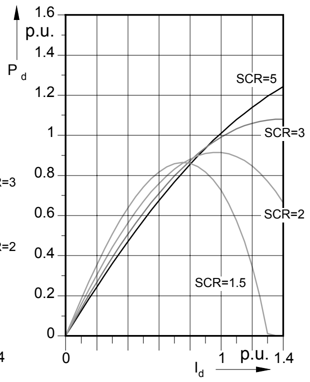
To analyse the steady-state stability of the two concepts, the Maximum Power Curves (MPC) are often used [6]. The theoretical curves show the maximum transmitted power when the inverter is operated in minimum extinction angle control mode at a certain SCR value of the ac network. All other values like tap changers, shunt capacitors and reactors are kept constant. The ac bus voltage is not controlled.

After a certain operation point an increase of dc current results in a decrease of transmitted power due to a higher consumption of reactive power. Hence the increase in dc current is smaller than the reduction of the ac voltage. The power transmitted at this operation point is called the Maximum Available Power (MAP). For a converter operated in constant power control mode the MAP point is the border between stable and instable operation of the system.

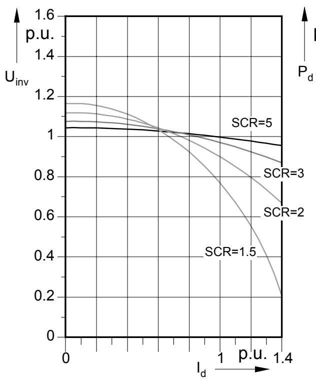
In the Fig. 5 b. and d. the MPCs are shown for both HVDC technologies at different ac system strengths. The corresponding ac bus voltages U_{inv} are presented in the graphs besides in Fig. 5 a. and c.



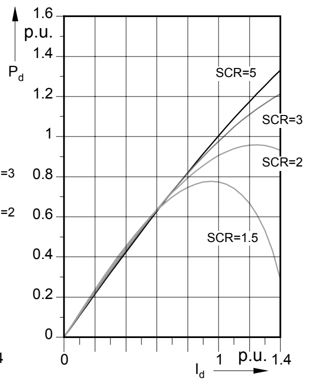
a. U_{inv}=f(I_d), HVDC



b. P_d=f(I_d), HVDC



c. U_{inv}=f(I_d), CCC



d. P_d=f(I_d), CCC

Fig. 5: U_{inv} and P_d as a function of dc current depending on the SCR

When using the CCC concept the gradient of the ac voltage is smaller compared to the conventional HVDC converter. This leads to a more stable operation expressed in a MAP point at a higher value of dc current. The MPCs show this increase of stability.

Even at a SCR value of 1.5 the converter can be operated up to rated dc current without loosing stability. Yet the operation at a strong inverter network (SCR = 5) shows a difference between the two concepts. From the graph of the ac bus voltage can be seen that an operation without switchable filter components can be realised over the whole dc power range.

If the network strength is changed until the nominal operating point coincides with MAP, the corresponding short circuit ratio is termed the critical SCR (CSCR). The CSCR can be expressed as follows [8]:

$$\mathrm{CSCR} = \frac{1}{U_{inv}^2}\left[-Q_d + P_d \,\mathrm{ctg}\frac{1}{2}\left(90° - \lambda - u\right)\right] + \frac{Q_c}{P_{dcN}} \quad (1)$$

For the HVDC system the CSCR can be calculated to $CSCR_{conv}$ = 2.19, whereas the CCC's CSCR is determined to 1.39. This suits to MPSs for SCR = 2 for the conventional converter respectively SCR = 1.5 for the CCC presented in Fig. 5.

IV. TRANSIENT PERFORMANCE

Conventional HVDC and CCC converter are now compared with respect to their transient behaviour. The reaction to a three phase ac bus fault and a reduction of the dc power setpoint are investigated.

IV.1. THREE PHASE AC BUS FAULT

Typical faults are applied to both system models designed in chapter II. The transmission systems are operating at the nominal operation point with P_{rd} = 4000 MW. For the simulation the transient simulation program EMTDC / PSCAD is used. To show the performance after a three phase ac bus fault at the inverter side of the converters, the dc current and voltage, inverter firing angle and the inverter ac bus voltage U_{inv} are presented in the Fig. 6 and 7.

After 0.1 s the fault occurs and is extinguished after 0.05 s which can be seen in the waveform of U_{inv}. After an initial overcurrent the dc current is brought to zero by the converter control. When the fault is extinguished, both systems recover to their nominal values.

The overcurrent at the beginning of the CCC is slightly smaller compared to the conventional converter. During the fault the waveforms of dc voltage and current of the CCC are more smooth due to better damping.

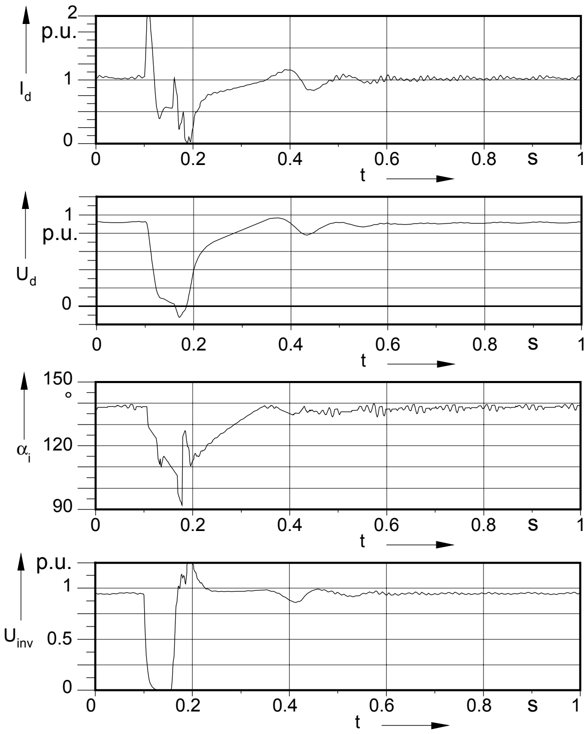


Fig. 6: Recovery from three phase ac bus fault at HVDC inverter

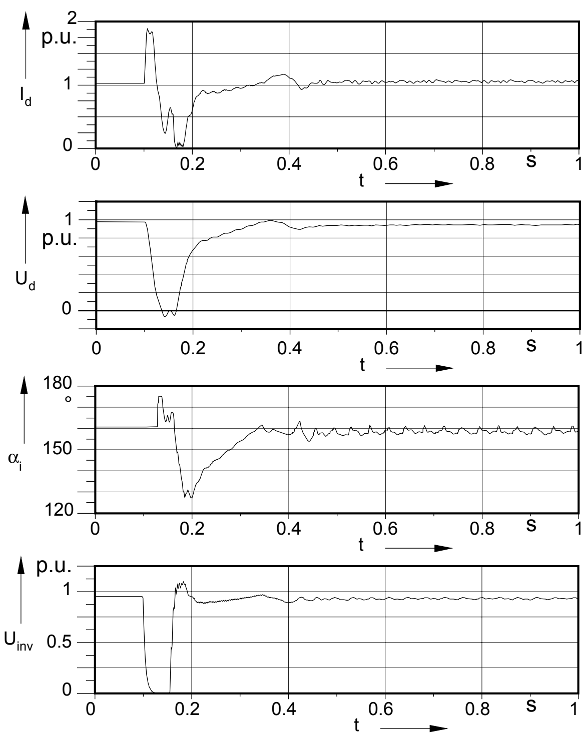


Fig. 7: Recovery from three phase ac bus fault at CCC inverter

The recovery times of the dc power of CCC and conventional system are nearly similar. 90 % of the power is restored after 130 ms.

After the fault is cleared the variables rise to the values of the former operation point. The inverter bus voltage U_{inv} overshoots its nominal value. The voltage overswing in the CCC system is lower. The transient response of the voltages and current is better damped than using the conventional HVDC technology.

IV.2. DC POWER REDUCTION

As a second transient event the response to a reduction of the power setpoint for the power controller is analysed. The power is decreased from nominal value to 0.75 P_{rd}.

In Fig. 8 and 9 the transient behaviour of the dc voltage, the dc current and the inverter bus voltage is shown. The duration of the simulation is one second, the event takes place at 0.1 s.

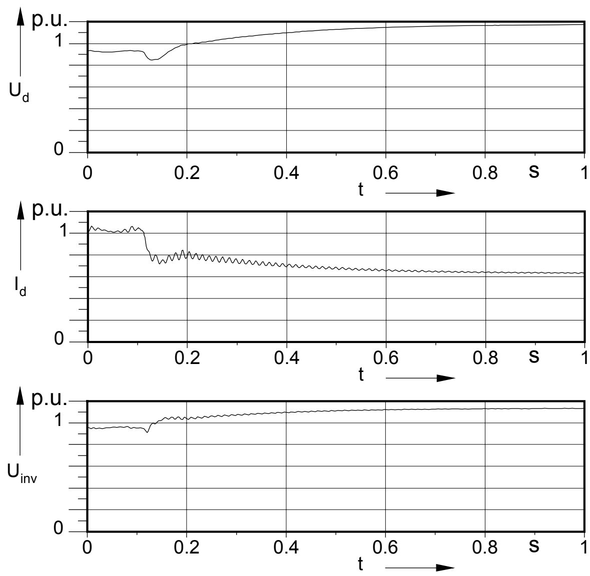


Fig. 8: Load reduction of 0.25 P_{rd}, HVDC

Due to the decrease in reactive power consumption the ac bus voltage at the inverter rises. Hence U_d is increased about 20 %. The power controller reduces the dc current to about 0.65 I_{rd}. Hence a reduction of 25 % in dc power is followed by a decrease of I_d of 35 %.

The waveforms of all graphs show a good damping characteristic. There is no overswing in the voltage waveforms. The dc current shows a high frequency oscillation. However U_{inv} is increased to a value that is not acceptable for steady-state operation, so the compensation capacitors or an ac filter has to be switched off.

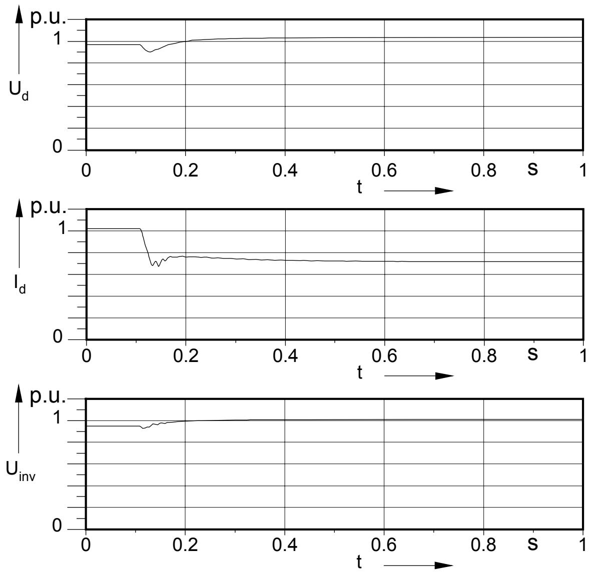


Fig. 9: Load reduction of 0.25 P_{rd}, CCC

Compared to the conventional HVDC the transient response of the CCC to the same event is shown in Fig. 9. The voltages U_d and U_{inv} are nearly kept constant. Their value is increased by less than 10 % indicating only a small reduction of the reactive power consumption.

The inverter bus voltage remains in the given voltage range for acceptable converter operation. The dc current is reduced to above 70 %. So the converter's behaviour results in an improved steady-state operating point.

Like the conventional HVDC system the CCC doesn't show any overshoot characteristics and the waveforms of the graphs are well damped.

V. Conclusion

In this paper two possibilities for the interconnection of the power systems of Eastern and Western Europe are shown. The CCC as a new concept of HVDC transmission system is presented.

The basic design parameters for a high power transmission system are introduced. The maximum rated dc power is limited to 4000 MW and the distance is about 1000 km. For both technologies a model system for steady-state and transient simulations is designed and described. The differences in the specification of the converter parameters are described. Here the design of the ac filters and the installed reactive power is important.

The steady-state performance is analysed by examining the reactive power consumption and the Maximum Power Curves. The shift of the MAP and hence the smaller CSCR indicates the improved steady-state behaviour of the CCC system.

For investigating the transient performance of both HVDC technologies, a three phase ac fault at the inverter busbar and a reduction of the DC power are applied to the system models. The recovery time from the fault is nearly the same, but the waveforms show a better damping characteristic for the CCC. The response to the decrease of the DC power setpoint show a faster reaction. Here the waveforms are better damped, too. In contrast to the conventional HVDC, the ac bus voltage at the new operation point, reached by the CCC, is within an acceptable range. Therefore switching of compensation devices is omitted.

These investigations show advantages of the CCC in its steady-state and transient behaviour especially when feeding into a weak ac network.

VI. References

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