Transformerless Active Voltage Quality Regulator Using Parasitic Boost Circuit

Miss Amruta kapse[1], C. M. Bobade[2]

[1] *PG Student, Department of Electrical Engineering, G.H. Raisoni college of Engineering, Maharashtra, India*
[2] *Assistant Professor, HOD. Department of Electrical Engineering, G.H. Raisoni college of Engineering, Maharashtra, India*

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Abstract - *Power systems are always subjected to some or the other kind of fault, thus affecting the quality of power being supplied to consumers. Power quality incorporates several aspects: overvoltage, voltage sag/swell, harmonics, interruptions, etc., which may last only for a few cycles, but can damage industrial as well as domestic equipments. Voltage sag is a temporary drop in voltage below 90% of the nominal voltage level and lasts for 50 to 170 milliseconds. There should not be any confusion between voltage sags and brownouts, which are reduction in voltage lasting from a few minutes to hours. This paper proposes novel topolog to mitigate long duration deep voltage sag, and the highly improved compensation ability is achieved by the unique placement of shunt convertor acting as a parasitic boost circuit. The proposed transformerless topology is very cost effective solution to voltage sag problem as compared to traditional dynamic voltage sag restorer, which includes bulky transformers. A dc-link adaptive control method is adopted to ensure high operational efficiency. To verify the feasibility of proposed system simulation as well as experimental results are presented.*

Key Words: Parasitic boost circuit, dynamic voltage restorer (DVR), long duration deep sag, brownouts.

1. INTRODUCTION

The operation of sensitive electronic devices goes on smoothly as long as the voltage of electricity supplying to them stays within the specified range. There are several types of voltage fluctuations. Some of them are voltage surge, sag, spikes, harmonic distortion and momentary interruptions. Voltage sag is proving to be most significant power quality problem to the large industries as well as domestic equipments. As the sensitive electronics loads are increasing, the problem of voltage sag cannot be neglected. Paying attention to this problem is a need of today's era, because they may cause loss in production and also finical loss of industry. Along with loss in production, voltage sags also damage equipments reducing their efficiency, which results in a lower quality product and reduced customer satisfaction. Lot of wastage of money due to this power quality problem has increased the interest of many researchers over the years, to mitigate the voltage sag by developing various compensating devices.

There are mainly two sources of voltage sag 1. External source 2. Internal source. External source is one which starts sag on utility lines up to your facility. Though the utility takes all the possible efforts to provide clean and consistent electric power to their customers, there are many things that can cause voltage sags. Storms are the main cause of external voltage sag. A heavy storm striking the power line may lead to many power quality problems. Internal source of sag production lies within your facility. Abrupt increase in load is also the cause of voltage sag, motor starting event, or turning on of heaters, etc. are the internal sources of voltage sag production. The majority of sages are generated inside a building. For example, in residential wiring, the most common cause of voltage sags is the starting current drawn by refrigerator and air conditioning motors. Understanding sources and reasons of voltage sag is a necessary thing. Regardless of source is internal or external one should start taking cost effective solution for the utility.

This paper introduces a novel active voltage quality regulator with the parasitic boost circuit, which is capable of providing specified voltage to the utility consumers without much increase in cost, volume and complexity. Many customer power devices to mitigate the voltage sag introduced in [2]. The inverter based regulators and ac-ac convertors are the general classification of voltage sag regulators [9] -[10]. The series connected device is an example of inverter based regulator topology. Dynamic voltage restorer is the traditionally used SD topology and has been widely studied. Different DVR topologies and their comparison have done in [5]. Also the discussion on DVR topologies has done in [3]. However, the bulky transformer does not make DVR affordable to use for long duration voltage sag. To eliminate this problem a transformerless dynamic sag corrector topology has been adopted [10]. The dc-link storage capacity of DySC topology limits the compensation of deeper voltage sag. In this paper, the position of shunt converter is on load side where, in DySC shunt converter is on the supply side. Because of these structural changes, shunt converter together with the series converter formed a boost charging circuit and the dc-link voltage will be charged to exceed the peak value of the supply voltage. Thus obtained module of the PB-AVQR topology. This paper proceeds with the introduction of operating modes of proposed topology and its working principle, then the parasitic boost model is provided followed by simulation and experimental results are provided.

2. LITERATURE REVIEW

The most studied voltage regulator topologies are generally classified into two groups as the inverter –based regulators and direct ac-ac converter.

The series connected device (SD) falls under the group of inverter based regulators. Basically series connected device compensate the voltage by injecting the missing voltage in series with the grid [2]. There are many SD topologies, but commonly used SD topology is dynamic voltage restorer. The operating principle, power circuit topologies, mathematical modeling, control philosophies and applications of DVR for power quality improvement has been discussed in [4]. The first section of this paper has described the basic operation and working principle of the DVR. The DVR injects the independent voltages to restore the line voltage to sensitive loads from sags caused by unsymmetrical line-to-ground, line-to-line, double-line-to-ground and symmetrical three phase faults said the author. In a second section various topologies for DVR has been given according to the location of DVR, converter type, energy source, filter and trasnformerless DVR gas also been discussed. The last section was of mathematical model followed by a conclusion The DVR consists of a set of series and shunt converters connected back-to-back, three series transformers, and a dc capacitor installed on the common dc link [4]. The parameters of electrical energy such as voltage amplitude are very important, particularly from the viewpoint of the final consumer and sensitive loads connected to the grid. Author classified the voltage compensators into three groups, first is electromagnetic. This group has included conventional electromagnetic transformer with tap changer. The second group is Electric group, under this group AC-AC PWM converter and AC/DC/AC converter fall. In third group called hybrid group, conventional transformer and in that combination of AC/DC-/AC converter were used. Simulation results, theoretical analysis and experimental test results from 2KVA laboratory model has been presented. This paper has presented the steady and transient-state properties of the three-phase voltage compensator [7].

The new inter phase ac-ac topology that has been proposed [11] does not need a storage device. A single phase compensator has designed with two transformers and two choppers. The required voltage is made available by controlling the duty cycle of each ac chopper. The Paper provides analysis, simulation results and also verification through prototype. The logic used in other sag supporters of correcting the sag by drawing power from affected phase itself further worsen the severity of the sag. But in the proposed topology the input power is taken from the other two phases and not from the affected phase.

The voltage sag supporter is independent of other two phases, and this is to be taken into considerations. The proposed method suggested being very reliable and cost effective due to the absence of any storage device. Further real power injection and ride through capability has not compulsory. Working principle for this controller was also simple. Unbalanced sag compensation has also possible with proposed topology. There were different symmetrical topologies of single phase AC/AC Semiconductor transformers which performs the operation of voltage sag mitigation [12]. The review of these topologies covered both non-isolated and isolated one as well as single or two-quadrant structure. Furthermore the averaged models, their four terminal chain parameters and outlined some exemplary applications of presented AC voltage transformation circuits have shown. An AC-DC-AC converters have been in use from a long time, though they are having good efficiency, these converters include large electrolytic capacitor, in the DC bus. This is the main concern while reliability took into consideration. Many converter configurations had already in use such as the buck, the boost and the full bridge converters, as discussed earlier [12]. The buck-boost converter for voltage sag and swell mitigation can only be used if transformer is included, which has increased the volume of these converters. To have a solution on to this the AC/AC based on Cuk configuration has been presented in [13]. As per said paper, since Cuk configuration is transformerless it lend itself to a compact and lightweight construction.

3. PROPOSED PB-AVQR MEHODOLOGY

As shown in Fig. 1, the PB-AVQR topology is mainly consists of five parts, including a static bypass switch (VT1, VT2), a half-bridge inverter (V1, V2), a shunt converter (VT3, VT4), a storage module ($C1, C2$), and a low-pass filter (Lf, Cf). In normal operating conditions, i.e. when there is no occurrence of sag, the static bypass switch is controlled to switch ON the normal grid voltage and supply it directly to the load. After the detection of abnormal condition, the static switch is OFF and that will control the inverter to inject a desired missing voltage in series with the supply voltage to ensure the power supply to sensitive loads. The two different kinds of control strategies are proposed in this paper. Which are, when the grid voltage is less than rated voltage, an in phase control strategy is adopted and a phase-shift control is adopted when the voltage is higher than nominal voltage. This is the basic operating principle of PB-AVQR topology.

Working principle of PB-AVQR is different from DySc due to the structural difference made in PB-AVQR, with load side connected shunt converter. After analyzing the proposed module it is seen that both the operating states of the switches (V1, V2) and the trigger angles of the thyristors (VT1, VT2) should be taken into consideration.

So, modification takes place in the proposed module and a simplified PB-AVQR (SPB-AVQR) circuit is formed as shown in Fig. 2. The only difference between two is that, the two thyristors (VT3, VT4) in the proposed PB-AVQR are replaced by two diodes (D1, D2).

The diodesperforms uncontrollable operation and thyristors perform a controlled operation. That is to say, the dc-link voltage of the SPBAVQR represents the upper limit of the dc-link voltage in the PB-AVQR structure. So, theoretical conclusions drawn with the SPB-AVQR are basically applicable to the PB-AVQR.

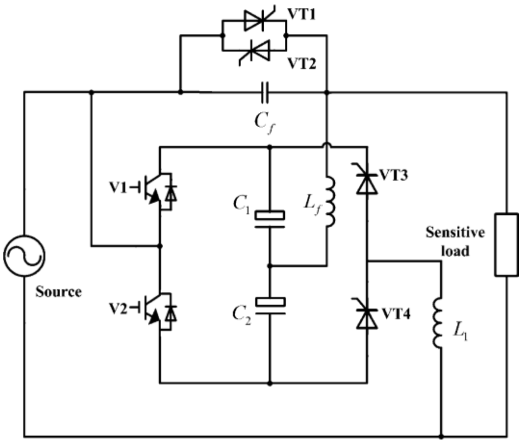


Fig – 1: Proposed PB-AVQR topology

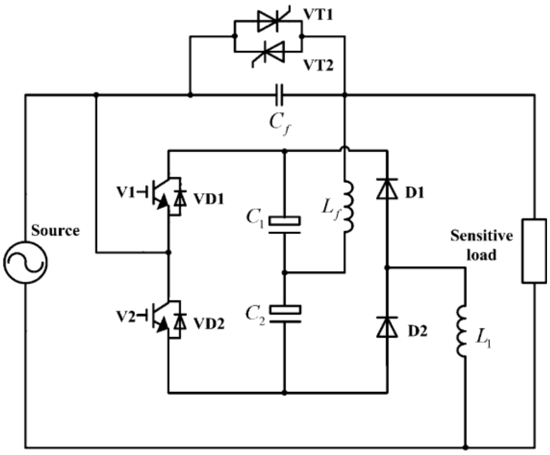
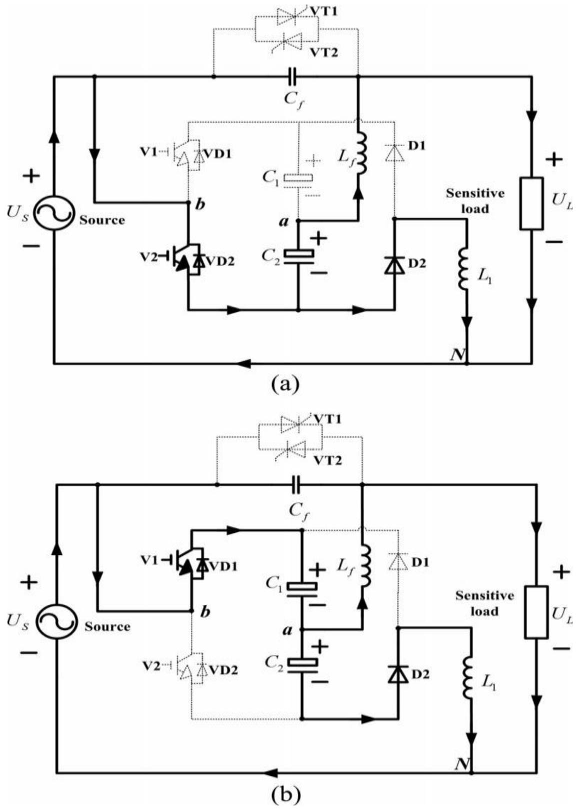


Fig -2: SPB-AVQR topology

As the changes have done in PB-AVQR circuit for simplification of understanding, the working principle of SPB- AVQR remains the same as PB- AVQR. It can be seen from Fig 2 that the dc-link voltage will now affect by the on/off status of switches this is because switches V1 and V2 are now also the part of a parallel circuit. So for understanding the working principle of the SPB-AVQR, it is necessary to know about the turn on and turn off condition of the compensation process. Within one switching cycle during the positive and negative half-cycle of the sinusoidal supply voltage, four different operating conditions of the SPB-AVQR is shown in Figs. 3 and 4. Both the compensation process and charging process can be explained based on these operating conditions.

In Fig. 3 and Fig 4, the solid line means that there is current flowing through and arrows depict directions. Operating conditions during the positive half-cycle are illustrated in Fig. 3. When V2 is switched on, as shown in Fig. 3(a), L1 is charged by the grid voltage via the diode D2 and the capacitor *C*2 discharges to maintain the load voltage. As shown in Fig. 3 (b), when V2 is switched off, the energy stored in the inductor during the early period is released to dc-link capacitors *C*1 and *C*2 through VD1 which is the antiparallel diode of V1.

Operating conditions during the negative half-cycle are given in Fig. 4. When V1 is switched on, as shown in Fig. 4(a), the inductor *L*1 is charged via the diode D1, and the load is compensated by the capacitor *C*. When V1 is switched off, as shown in Fig. 4 (b), the energy stored in *L*1 is released to capacitors *C1* and *C2* through the diode VD2, which is the antiparallel diode of V2. So, in each half-cycle of the supply voltage, one capacitor of the dc-link get discharged to supply the energy needed for the compensation, and the charging process is responsible to provide this energy, which is discussed earlier.



(a)

(b)

Fig- 3: Operating conditions during positive half-cycle. (a) V2 switched on. (b) V2 switched off.

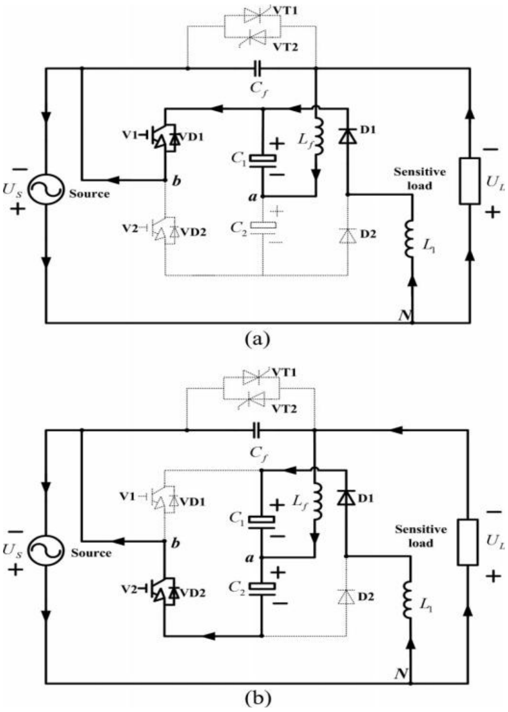


Fig –4: Operating conditions during negative half-cycle. (a) V1 switched on. (b) V1 switched off.

The compensation ability of SPB-AVQR is theoretically unlimited as long as the grid is strong enough to provide the power that is needed, because it is seen that the charging circuit of the proposed configuration works exactly similar to boost circuit and the dc-link voltage in this situation is controlled by the duty ratio of the two switches. However, as because the boost circuit depends on the series inverter, and the two switches are actually controlled according to the missing voltage, there still exist some limitations.

Fig. 5 shows the circuit diagram of designed hardware model for PB-AVQR. From the circuit diagram it can be seen that the transformer supply is given to the 555 timer IC which helps to provide the gate pulse required for operation of switches used and also to the input terminal of circuit. By varying the input voltage corresponding output voltage can be measured. The hardware circuit diagram for SPB is exactly similar only change is that diodes are used as a shunt converter instead of thyristors. Figs. 6 and 7 show the pictorial view of hardware model of both PB and SPB-AVQR.

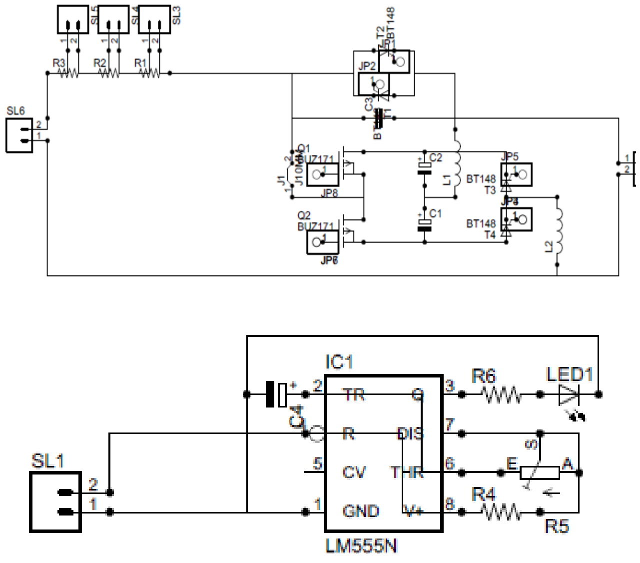


Fig.- 5: Hardware circuit diagram of PB model

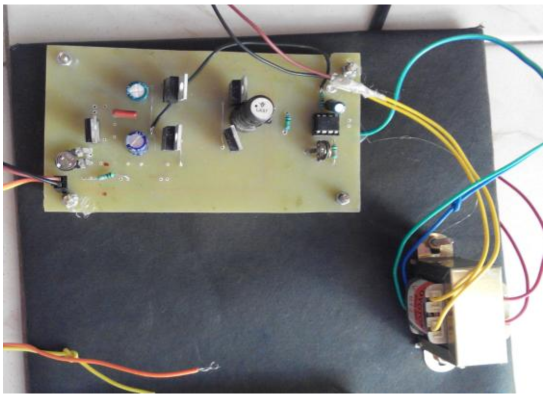


Fig -6: Pictorial view of PB-AVQR model.

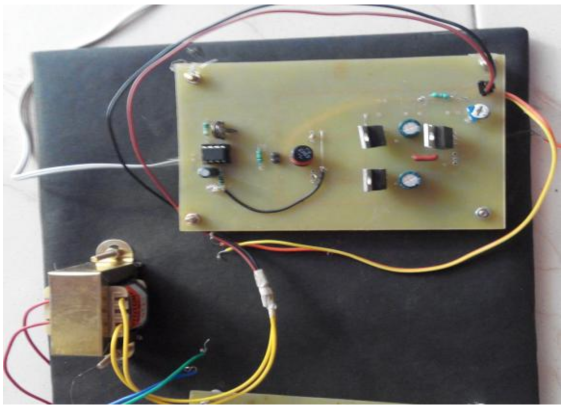


Fig -7: Pictorial view of SPB-AVQR model.

3.1 AVQR Topology

In the proposed parasitic boost circuit, the dc-link adaptive control logic applied is helpful in maintaining the required voltage for specified duration of time. But the normal AVQR circuit is designed without applying the dc link adaptive control logic. The working of this AVQR circuit remains the same as PB-AVQR except that, whatever lacking dc link voltage provided with use of dc link adaptive control method is not applied. Like SPB-AVQR, the special active voltage quality regulator is also developed using diodes for shunt converter. The performance of both the modules is analyzed and compared with proposed topology.

4. RESULT ANALYSIS

The simulation results of parameters for proposed PB-AVQR and SPB-AVQR topology are presented in this section. A hardware prototype is also presented in order to show the validity of designed modules. The simulation results are based on the MATLAB software. Also the comparison between the operating efficiencies of both the modules is presented with the help of designed prototype.

4.1 System Parameters

The main parameters which are needed to be designed are, the dc-link capacitor $C1$ /$C2$, the filter inductor Lf , the filter capacitor Cf, and the charging inductor $L1$.

Table -1: System Parameters

Description	Parameters	Real Value
Nominal voltage	Vref	220V
Line frequency	*f0*	50Hz
Switching frequency	*fs*	15KHz
DC-link capacitor	C1/C2	4700μF
Filter inductor	*Lf*	1.5mH
Filter capacitor	*Cf*	20μF
Charging inductor	L1	2mH

The Key parameters of PB-AVQR and SPB-AVQR are listed in the above table.

4.2 Simulation Results of PB and SPB-AVQR

Fig. 8 and Fig 9 shows the simulation results of the PB-AVQR topology with different supply voltages. It is seen from Fig. 8 the voltage drops to 180V at 0.05 sec, at this time the dc-link voltage is high enough for the compensation of voltage drop of 180V. The active power during the steady state compensation is 4.9 KW, which means that a load of this specification can be compensated for the voltage sag event. The reactive power during steady state compensation is 0.75 KVAR with 180V supply. The reactive power is injected for a very short time due to sudden change in supply voltage, so as to provide the voltage level necessary for the active power to do work.

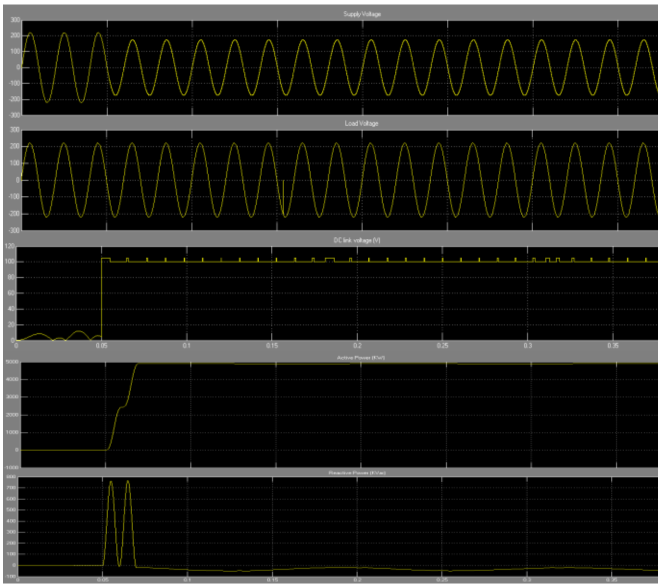


Fig -8: Simulation results of PB-AVQR for voltage supply of 180V.

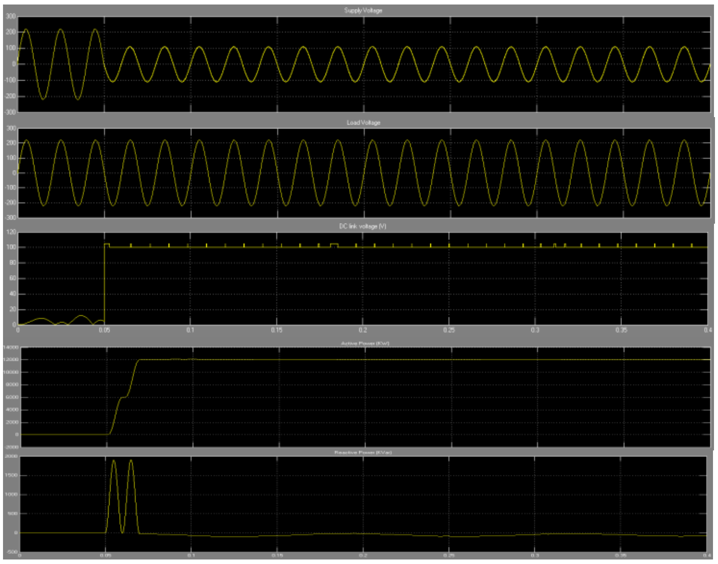


Fig -9: Simulation results of PB-AVQR for supply voltage of 100V.

When the supply voltage drops to 100V as shown in Fig 9, the dc –link voltage is still able to maintain the load voltage to 230V. The active power during this supply voltage is

12KW. As the supply voltage suddenly drops to 100V after 0.05 sec, the reactive power injected from this instant of time is 1.9KVAR. The reactive power is higher in PB-AVQR topology and provides the necessary voltage required to maintain the active power supply with the help of dc-link adaptive control method

Fig. 10 and Fig. 11 show the simulation results of SPB-AVQR for the supply voltage of 180V and 100V. As per the discussion made in section 2, the SPB follows PB-AVQR topology, the results of simulations in Fig. 9 and Fig. 10 are completely applicable to PB-AVQR results.

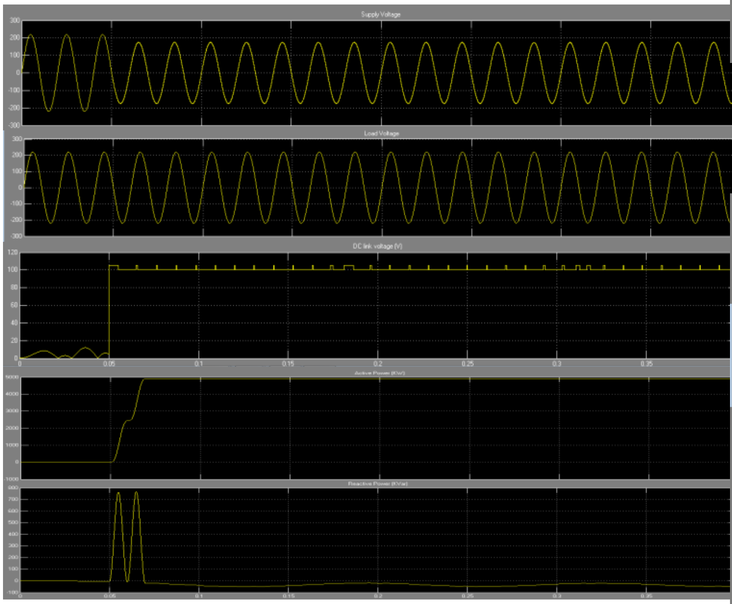


Fig -10: Simulation results of SPB-AVQR for voltage supply of 180V.

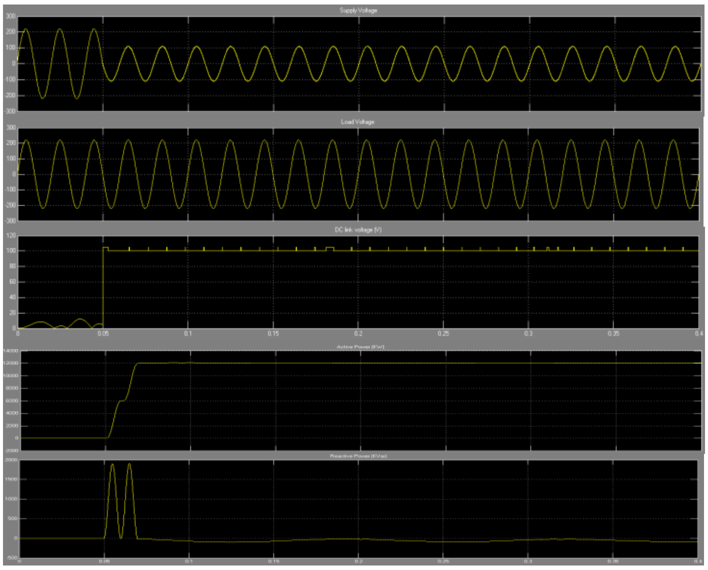
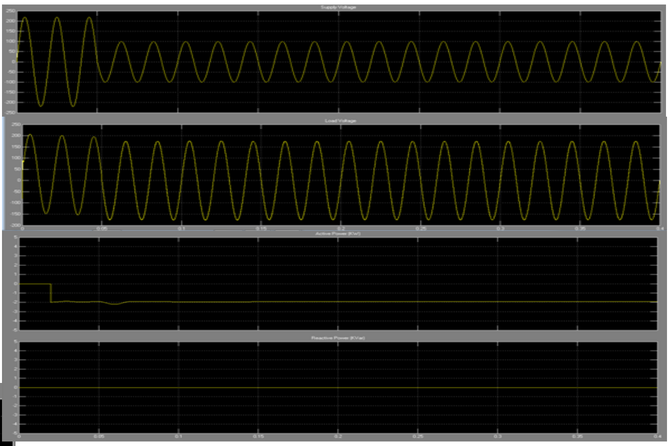


Fig -11: Simulation results of SPB-AVQR for supply voltage of 100V.



ig- 12: Results of AVQR for the Supply Voltage of 100V

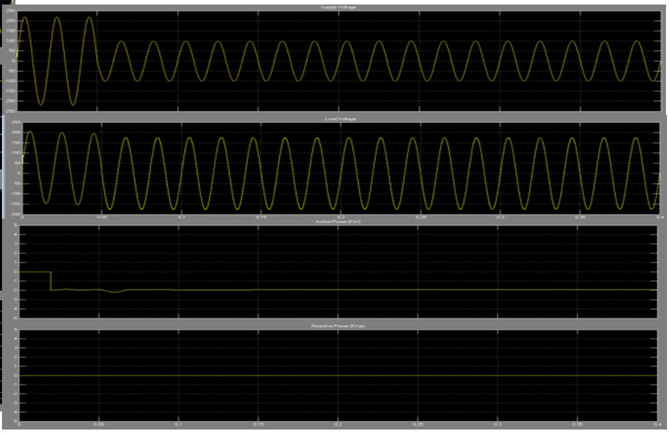


Fig- 13: Results of S-AVQR for the Supply Voltage of 100V.

Fig 12 and Fig 13 shows the results of AVQR and Special AVQR circuit at the voltage sag of 100V. From the results it is seen that the dc-link capacitors starts discharging and after the occurrence of sag at 0.05sec, it maintains the constant value and we can see the load voltage is remaining constant to 175 volts throughout the period. This shows that after the occurrence of sag, the normal AVQR as well as S-AVQR system are not able to maintain the constant load voltage.

Fig. 14 shows the result of DySC topology used for the compensation of voltage sag [10]. Dynamic sag corrector is also one of the voltage compensator. The three types of DySc models have been discussed in [10]. The single phase DySC implement the single phase inverter to operate in by-pass and boost mode thereby claims to provide boost up to 100%. For the lower power, three phase 4-wire application, a three phase ProDySC was ralized from single phase DySC. For the application requiring ultra reliable utility power Mega DySC combinations were designed. The results are shown in Fig. 14. The supply voltage lowers down after 0.05sec and goes on fluctuating in the range of 100 volts. The use of dynamic sags compensator has injected missing voltage and thereby maintained the load voltage. However, it can maintain the load voltage up to 0.3 sec and the proposed PB-AVQR topology can maintained load voltage up to 0.4 sec.

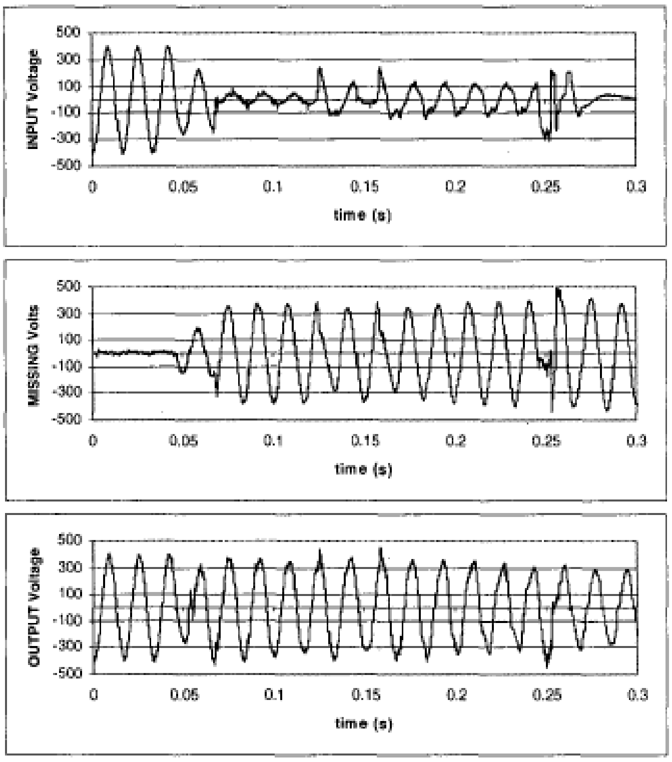


Fig -14: Simulation results of DySC topology.

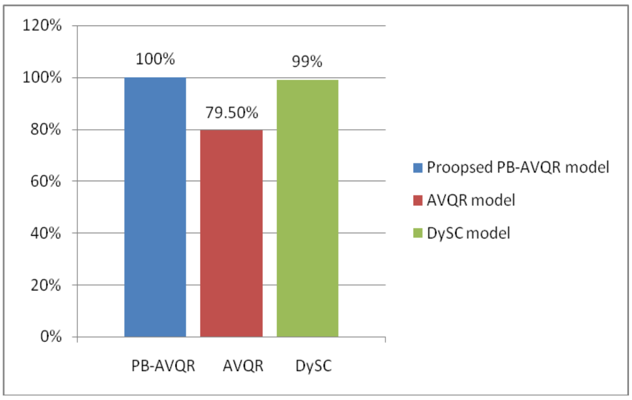


Figure -15 : Comparative Efficiency Graph of PB-AVQR, AVQR and DySC Models.

The simulation results of proposed PB –AVQR topology have shown the complete compensation of load voltage. This is because the dc link program developed will provide the necessary lacking dc- link voltage, which ultimately compensates the voltage sag occurred in the system. Thus, it gives 100% efficiency. But in case of the normal AVQR module, after complete discharging of dc link capacitors, the capacitors are not getting necessary boost to maintain the load voltage and thus the efficiency obtained is low as 79.5% as shown in Fig 15.

Table -2: Comparison Table of Three Modules

	Average voltage sag	Maintained voltage difference	Efficiency	Sag maintained duration
Proposed PB-AVQR module	100-200V	0V	100%	0.4sec
AVQR module	100 -200V	30V	79.5%	0.4 sec
DySc module	100 -200V	0V	99%	0.3sec

Table 2 shows the comparison between all the three modules based on their simulation results. Thus from comparative analysis of simulation results it can be seen that PB-AVQR has improved compensation performance for long and deep sag than DySc topology and normal AVQR module

4.2 Experimental Results

From the simulation results it can be seen that the SPB-AVQR completely follows the PB-AVQR, But practically they have the totally different control logics used on the load side to maintain the load voltage constant. This difference can be analyzed on the experimental basis, for that we have developed a hardware prototype of both PB and SPB. From that the efficiency curve of each topology is provided. The efficiency of PB –AVQR topology is calculated for the supply voltage ranging from 8 volts to 13 volts taking five points calculating their efficiency for each point, shown in Fig. 16. Similar is the case of SPB-AVQR, the five points are taken with the supply voltage ranging from 10 to 15 volts. On each point efficiency and ability to maintain the load voltage is tested, shown in Fig. 17.

It can be seen from Fig.18 that the efficiency of PB-AVQR topology is higher, i.e. 92% than the efficiency of SPB-AVQR topology which is 90%. This difference in efficiency between two topologies is because PB uses thyristors on load side which are controllable in nature and SPB uses diodes which are uncontrollable in nature.

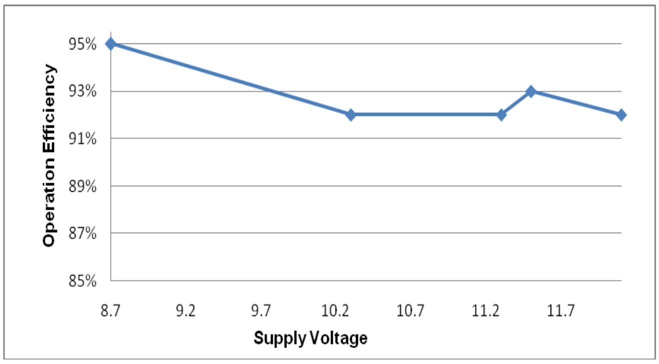


Fig. -16: Efficiency graph of PB-AVQR topology.

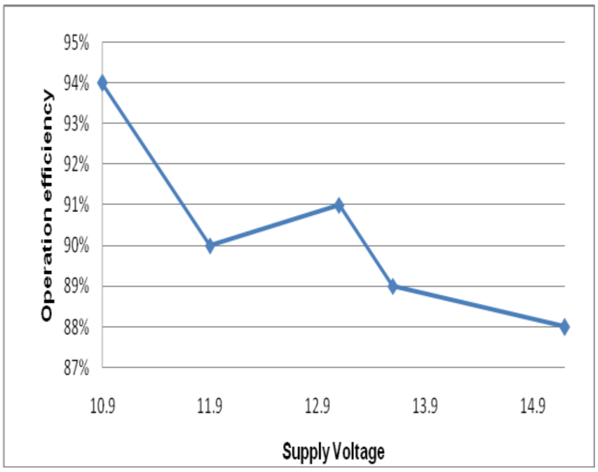


Fig -17: Efficiency graph of SPB-AVQR topology.

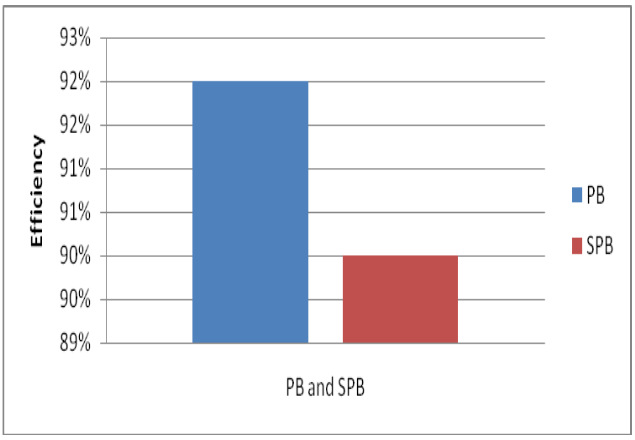


Fig – 18: Graph comparing efficiencies of both PB and SPB topologies.

4. CONCLUSION

A novel topology called transforrmerless active voltage quality regulator using parasitic boost circuit is studied. The proposed PB-AVQR topology design is obtained by making some structural changes in DySC configuration. Thus the compensation ability is highly improved without increasing the cost, volume and complexity. With the load side connected shunt converter and no use of transformer makes the PB-AVQR topology very cost effective solution for deep voltage sag than the traditional DVR topology. The working principle, operating conditions are explained. The simulation results at various supply voltage conditions are presented, to verify the feasibility of proposed topology at these voltages. The operating efficiency differences between PB and SPB model is calculated and shown by performing experiments. The dc-link adaptive control method adopted, makes the operating efficiency of PB-AVQR higher than DySC topology, normal AVQR topology and SPB-AVQR topology.

Hence we can conclude that the proposed PB-AVQR topology have higher compensation ability and operating efficiency, which make it a unique solution for long and deep voltage sag.

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