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Mitigation of sag with transformerless active voltage quality regulator using FUZZY controller

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Abstract

Change from the rated level in the voltage causes the severe damage to the industries and sensitive loads. If deviation from the rated value is much more, it may be dangerous the domestic loads also. So in order to avoid this problem a series connected shunt structured transformerless circuit is designed where this may handle deep sags which are up to 50% of the rated values in voltage levels. A new design is proposed in order to compensate the voltage levels. High operation efficiency is obtained by this method of controlling due to application of the DC link voltage adaptive control method. The decrease in THD level and time of operation, increase in efficiency obtained due to usage of fuzzy controller, Analysis and the simulation results are presented in this paper.

1. INTRODUCTION

Power quality is the main important thing while an utility is supplying electrical power to the consumer. Even a small distraction in power quality may lead to heavy losses for commercial and industrial consumers. Mainly the decrease of voltage levels even for the small instant of time may create large financial problems, not only economical, if the sag occurs for the more time it leads to technical problems also. So deep sags for the larger interval of time cannot be ignored which are more intolerable than the shallow sags.

So there are many devices in existence for the compensation of these sags, mostly used devices are series connected in the line where their duty is to inject the missing voltage into the line. Actually these compensating devices are divided into two groups, they are the inverter-based regulator and direct ac–ac converters. The series connected devices mostly comes under the category of the voltage sourced inverter based structures. Under these series connected devices Dynamic Voltage Regulator(DVR) is the one, which is widely used. There are different types of DVR structures where they can compensate even the more deep voltage sags. In the structure of DVR series connected transformer is the important one which is mainly used to inject the required voltage into the circuit. But these DVR structures are more costly due to presence of transformers, which is not ignorable for low power applications and for the distribution systems which are working on the low line frequency, and these DVR’s cannot compensate the deep voltage sags.

So in order to reduce the cost, and for compensating the deep sags a new topology known as Parasitic Boost Active Voltage Quality Regulator(PB-AVQR) is introduced. In this structure there is no series transformer. Instead of series transformer elements like inductors and capacitors will help in injecting the missing voltage into the line. There are so many types of sag correcting structures. As this whole circuit working is based on the DC link voltages which is taken from the capacitors in the circuit. As there is no series transformer the cost of the these circuits is much less than the DVR.

But in the basic circuit, the sags deeper than the 50% of voltage cannot be compensated which exists for more time interval. So even the basic structure of Sag corrector circuit is good in compensation sometimes backup grid is needed to compensate the higher voltage sags. So some changes have been done in these structure in order to make it capable of compensating the deep sags which are occurring for more interval of time. The position of shunt converter and series converter are changed in such a way that DC link voltage can be charged more than the peak value, so that this structure can compensate the sags which are very deep and exist for more time. The changed structure of DySC will form the boosting circuit. So this circuit can be named as transformerless active voltage quality regulator with the parasitic boost circuit (PB-AVQR). The DC link adaptive control method is adapted in this circuit, so the high efficiency is obtained even for the low cost and less complex circuit.

2. WORKING PRINCPLE AND TOPOLOGY

Mainly this structure consists of five important parts namely bypass switch, filter circuit, half bridge inverter, shunt converter and storage module. Under the normal operating conditions bypass switch will be in ON state, whenever voltage levels varies from the actual value switch will goes into the OFF position and the compensating circuit will comes into the picture. The inverter will be controlled in such a way that it makes the compensating circuit to deliver the missing voltage into the line.

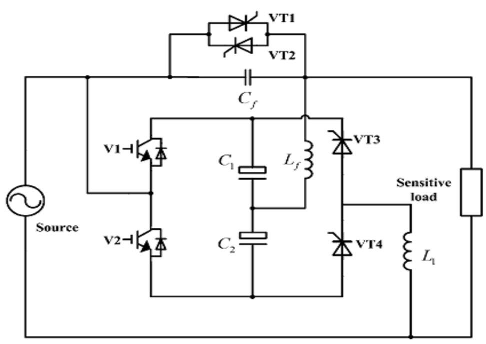

Fig. 1. Proposed PB-AVQR topology

But for the simplified analysis we can replace the Thyristors in the circuit by diodes, where the analysis will be same and circuit can be called as SPB-AVQR.

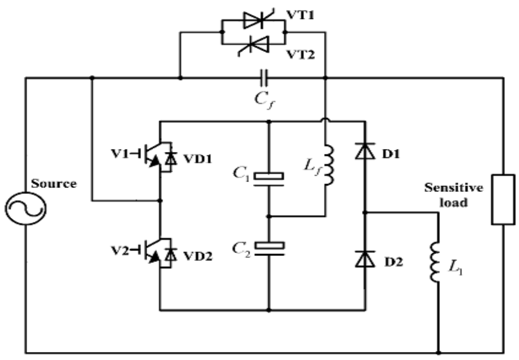

Fig. 2. SPB-AVQR Topology

The control strategy which we are using is sinusoidal pulse width modulation for the sake of triggering the power electronic devices. As V1 and V2 are also creating parallel circuit, their switching sequence will show much effect on the DC link voltage which indirectly show effect on the output voltage. So we have to understand the switching pulses generation for this V1 and V2.

We can have four different operating conditions based on the ON and OFF conditions of V1 and V2.

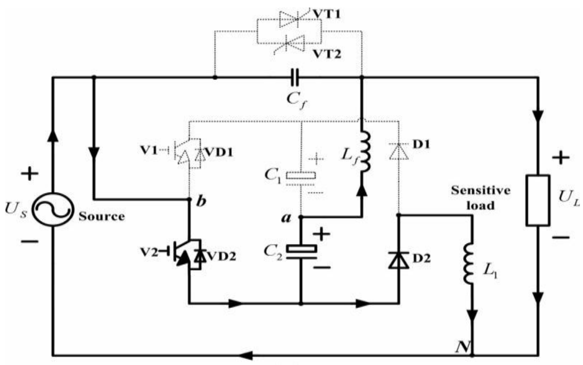

Fig. 3. Operating condition during positive half cycle (V2 switched on)

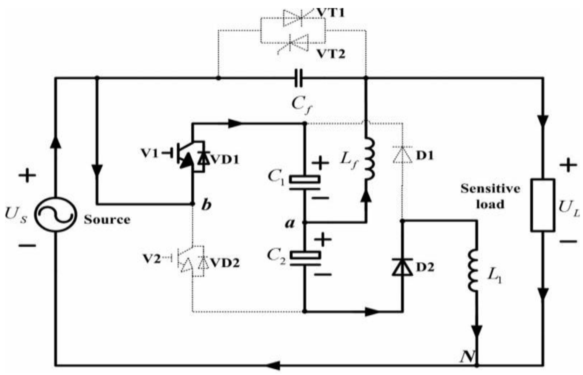

Fig. 4. Operating condition during positive half cycle (V2 switched off)

The above figures gives us operation of the circuit in the positive half cycle. In fig(3), when V2 is switched on, inductor L1 will be charged through diode D2 from the grid, in the mean time capacitor C2 will discharge the energy which will compensate the reduced voltage at the load side. When V2 is switched off, as shown in Fig. (4), the energy stored in the inductor during previous period is released to dc-link capacitors *C*1 and *C*2 through VD1 which is the anti parallel diode of V1.

During the negative half cycle of the voltage, when V1 is switched on the inductor L1 will be charged from grid through diode D1, and the compensating voltage will be supplied from the capacitor C1 and when V1 is switched off energy from inductor L1 will be released to C1 and C2 through VD2 which is anti parllel to V2. So the energy from the supply source itself will be used for the sake of compensation in both the half cycles via charging process.

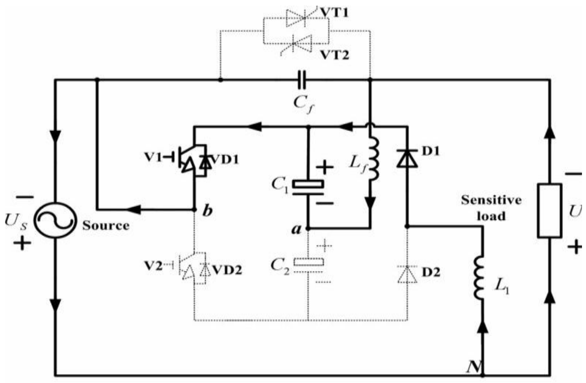

Fig. 5. Operating condition during negative half cycle (V1 switched on)

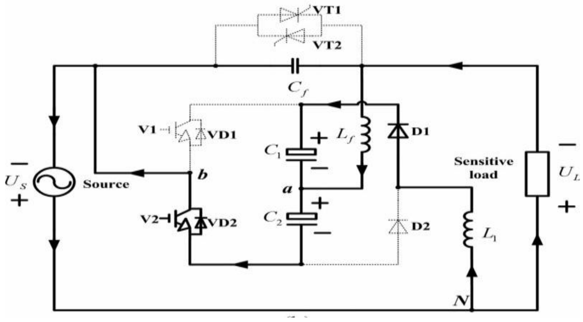

Fig. 6. Operating condition during negative half cycle (V1 switched off)

In the negative half cycle inductor L_1 is charged via D_1 through V_1 and compensation of load is done by C_1. When this V_1 is switched off L_1 will releases energy to capacitors C_1 and C_2 through the anti parallel diode of V_2. Soin each half cycle one capacitor will discharges the required energy which is actually obtained from the supply source via charging.

Here actually the compensation is mainly depends on the duty ratio given to the circuit. So theoretically compensation ability of the circuit is unlimited as long as supply is capable of supplying the power. But boost circuit is parasitic in nature on the series inverter and the two switches are controlled according to the missing voltage, so there exists some restrictions.

The switching harmonics will be controlled by L_f and C_f and smooth waveform will be obtained.

3. Theoretical analysis

DC link voltage is the key parameter which will decide the maximum injected voltage for the compensation. The relation between the DC link voltage and other system parameters and feasibility in mitigating deep sags will obtained based on circuit model.

As working principles of both positive and negative half cycles of the circuit are same we can analyze any of the cycles and implement the same to other. As we are using in-phase compensation the energy needed to maintain load voltage is given by

$$E_0=(T_0\Delta V/2V_{ref})P_0 \quad (1)$$

where$T0$ is the grid voltage period time, Vref is the rated rms value of the load voltage, $P0$ is the rated load power, and ΔV is the rms value of the missing voltage.

During steady state compensation the energy needed should be supplied from the supply itself. The simplified circuit model of circuit is illustrated in fig, where compensation loop including the filter and the load is ignored and only the charging circuit is considered.

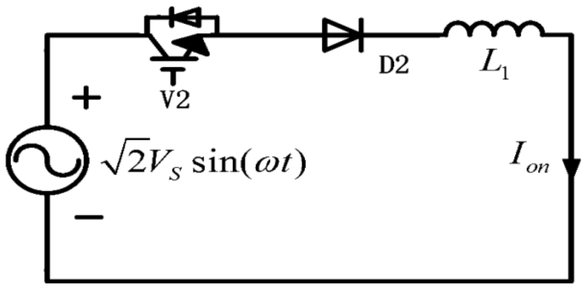

Fig. 7. Simplified model when V2 turned on

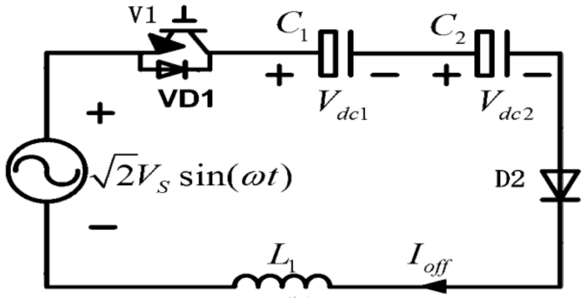

Fig. 8. Simplified model when V2 turned off

V_s is the supply rms voltage. The state equations are given by

$$L_1 \frac{dI_{on}}{dt} = \sqrt{2}V_s \sin(\omega t)$$

$$L_1 \frac{dI_{off}}{dt} = \sqrt{2}V_s \sin(\omega t) - V_{dc1} - V_{dc2} \qquad (2)$$

According to [2] and [3] the analysis will be simplified if some realistic approximations are carried out. then the above equations can be discretized as

$$L_1 \Delta I_{onn} = \sqrt{2}V_s \sin(\omega n T_s)t_{onn}$$

$$L_1 \Delta I_{offn} = [\sqrt{2}V_S \sin(\omega n T_s) - 2V_{dc}]t_{offn} \qquad (3)$$

where $t_{onn}$and t_{offn} are, respectively, the turn-on and turn-off time of V2 in the n_{th} switching cycle, Ts is the switching period, V_{dc} is the steady-state dc-link voltage, and ΔI_{onn} or ΔI_{offn} represents the variation amount in charging current during t_{on} or $toffn$. As the analysis is within the positive half-cycle of the grid, there exists a constraint: $n \leq T0/2Ts$. Apparently, t_{on} and t_{offn} here are actually the inverter's duty cycle and they can be expressed as (4) when two-level symmetric regular-sampled PWM method is adopted[5].

$$t_{onn} = \frac{T_s}{2}\left[1 + \frac{\sqrt{2}\Delta V sin(\omega n T_{s)}}{V_{dc}}\right]$$

$$t_{offn} = \frac{T_s}{2}\left[1 - \frac{\sqrt{2}\Delta V \sin(\omega n T_s)}{2}\right] \quad (4)$$

The charging energy provided by the grid in n^{th} switching cycle via boost circuit can be expressed as

$$E_{in\,n} = \frac{1}{2} L_1 \Delta I_{on\,n}^2 + L_1 I_{off(n-1)} \Delta I_{on\,n} \quad (5)$$

$I_{off}$and I_{on} are expressed as given in[1].
The energy provided in the n^{th} switching cycle can be written as follows

$$E_{inn} = \frac{T_s^2 V_s^2 A^2}{4L_1}\left(1 + \sqrt{2}BA\right)^2 + \frac{\sqrt{2}T_s^2 V_s A}{2L_1 V_{dc}} \times \left(V_{dc} + \sqrt{2}\Delta V A\right) \sum_{k=n_0}^{n-1} (\sqrt{2}V_{ref} C - V_{dc}) \quad (6)$$

Where
A= sin$\omega n T_s$

B= $\dfrac{\Delta V}{V_{dc}}$

C= $\sin(\omega K T_s)$

As we obtain E_1, added with n ranging from 1 to $T_0/2T_s$. The overall energy balance equation is given as

$$E_1 = T_s^2 V_s^2 \left(\sum_{n=1}^{\frac{T_0}{2T_s}} A^2 + 2\sqrt{2} B \sum_{n=1}^{\frac{T_0}{2T_s}} A^3 + 2B^2 \sum_{n=1}^{\frac{T_0}{2T_s}} A^4 \right) + \frac{T_s^2 \sqrt{2} V_s}{2 L_1} \sum_{n=n_0}^{n_s} \left[\left(A + \sqrt{2}BA^2\right) \sum_{k=n_0}^{n-1} \left(\sqrt{2V_{ref}C} - V_{dc}\right)\right] \quad (7)$$

I_{max} is expressed as

$$\frac{\sqrt{2}T_s V_s \sin(\omega n_{max} T_s)}{2L_1}\left[+\sqrt{2}B \sin \omega n_{max} T_s\right] + \sum_{n=n_0}^{n_{max}} \frac{T_s}{L_1}\left(\sqrt{2}V_{ref}C - V_{dc}\right) = I_{max} \quad (8)$$

Where n_{max} is the switching cycle when I_{offn} reaches its maximum value and n_{max} can be written as follows

$$n_{max} = ceil\left[\frac{T_0\left(\pi - arcsin\frac{V_{dc}}{V_{ref}}\right)}{2\pi T_s}\right] \tag{9}$$

As we cannot obtain the DC link voltage directly an iterative algorithm is given where *Ts*, *VS*, *T*0, *V*ref, *L*1, and *P*0 are all treated as constants.

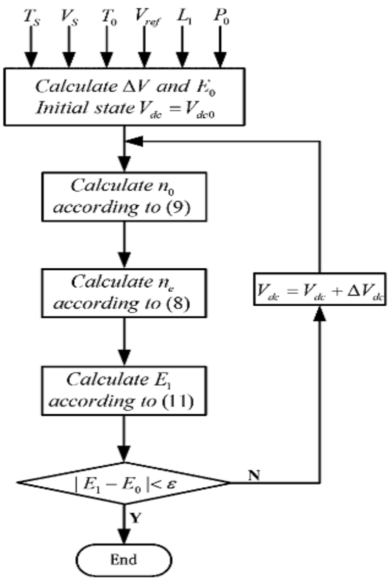

Fig. 9. Flow chart for calculating V_{dc}

But this theoretical analysis of SPB-AVQR may differ from PB-AVQR with small differences due to consideration of α forVT3 and VT4 in main circuit. the charging process begins after the VT3 or VT4 is triggered, so the initial superposition Instant n_0 in (11) is now determined by *α* denoted by *n*1 and the energy balance equation is written as follows

$$\frac{T_s^2 V_s^2}{4L_1}\left(\sum_{n=n_1}^{n_e} A^2 + 2\sqrt{2}B\sum_{n=n_1}^{n_e} A^3 + 2B^2\sum_{n=n_1}^{n_e} A^4\right) + T_s^2\sqrt{2}V_s\left(\frac{1}{2L_1}\right)\sum_{n=n_1}^{n_e}\left[\left(A + \sqrt{2}BA^2\right)\sum_{k=n_1}^{n-1}\left(\sqrt{2}V_{ref}C - V_{dc}\right)\right] = \frac{T_0\Delta V}{2V_{ref}}P_0 \tag{10}$$

$$n_1 = ceil\left(\frac{\alpha T_0}{2\pi T_s}\right) \tag{11}$$

Furthermore, the thyristors are triggered only once in each half-cycle and the current through them should be higher than the holding current to maintain the triggered state.

So, α is required to meet the constraint expressed as follows

$$\sqrt{2}V_{ref}\sin\alpha > V_{dc} \tag{12}$$

4. FUZZY Controller

Here the pulsing pulses generated must be controlled by using certain controller. Mostly in olden days PI controller is being used, but we can use the fuzzy controller in the place of PI controller where we can have certain advantages, The main advantage is that we can reduce THD to the minimum point.

Here in the usage of Fuzzy logic operation, membership functions are very important, where in this circuit we have seven membership functions.

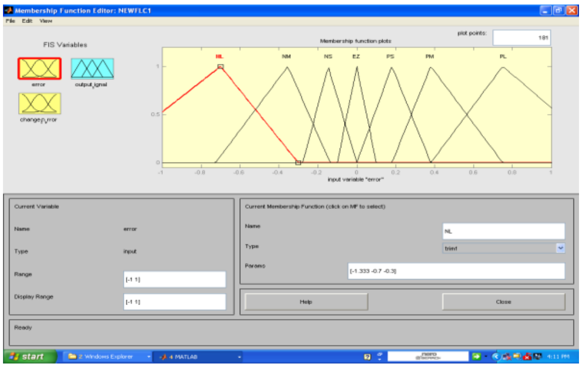

Fig. 10. Membership functions of Fuzzy

By using the fuzzy controller we can have less time of operation which is more efficient and reliable.

Training is given to fuzzy to compensate sags, that is the duty ratio of power electronic devices is changed according to sevieority of fault.

Based on the given set of rules the fuzzy controller will works. In this paper MAMDANI is used.

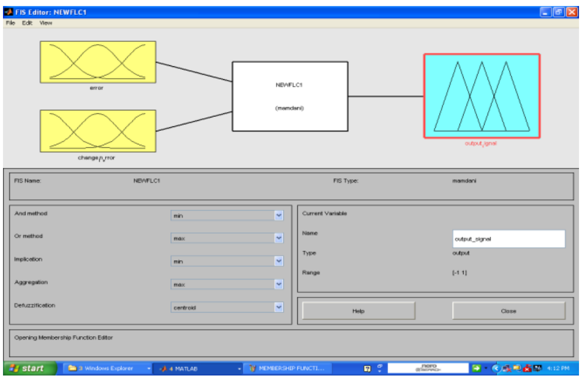

Fig. 11. Mamdani used Fuzzy controller

So whenever Sag occurs Fuzzy controller will change the duty ratio based on the amount of the voltage drop.

5. Simulation results

In order to show the validity of the proposed PB-AVQR, simulation results are presented in this section. The simulation results are based on the MATLAB software. The control method applied for the inverter is proposed in [4] and the control method for the thyristors is demonstrated in[5].

System parameters

The four main parameters which we have to design for the best operation of the proposed circuit are C_1 /C_2, L_f&C_f, charging inductor L_1.

The energy balancing equation which we have take into the consideration for above parameters are according to [1].

Table :1 System Parameters

Description	Parameters	Real value
Nominal voltage	V_{ref}	220V
Line frequency	f_0	50Hz
Switching frequency	f_s	15kHz
DC-link capacitor	C_1/C_2	4700μF
Filter inductor	L_f	1.5mH
Filter capacitor	C_f	20μF
Charging inductor	L_1	2mH

In this proposed circuit when the voltage drops to 180v at 0. 1 sec, circuit can compensate the sag. Even when voltage drops less than 100v at 0. 4sec this fuzzified circuit can compensate the deep sags, where asDySC cannot compensate less than 100v sag. The transient response can be improved by increasing the set value for DC link voltage.

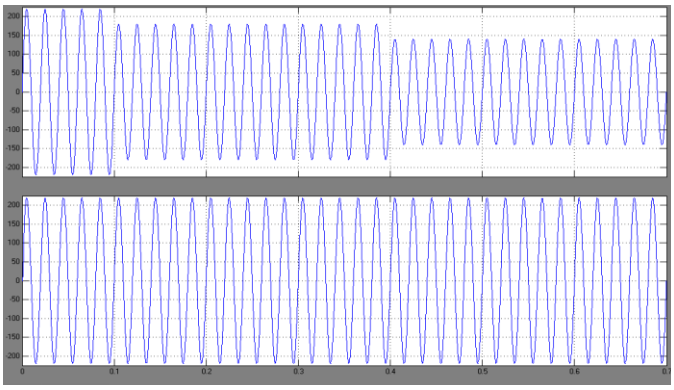

Fig. 12. Voltage waveform obtained after compensation of Sag (X-Axis:Time, Y-Axis:Voltage)

The fuzzy controller is used inorder to control the pulse so seven membership functions are given.
The THD value is much decreased after using fuzzy controller when compared to usage of other controllers like PI.

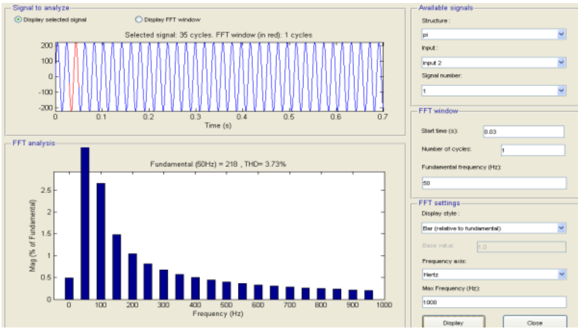

Fig. 13. THD obtained by PI controller (THD value3. 73)

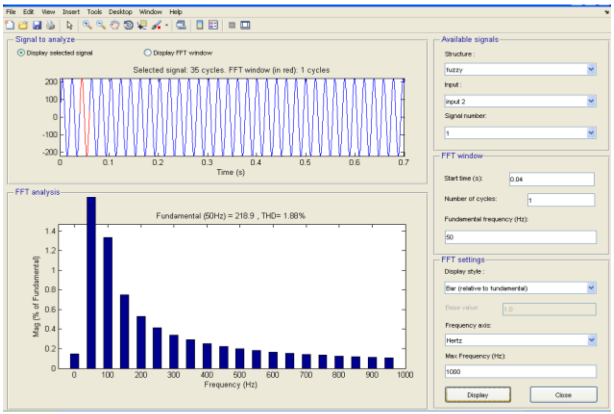

Fig. 14. THD obtained by Fuzzy controller (THD value 1. 88)

6. Conclusion

The proposed circuit Fuzzified transformerless boost circuit is a better solution for long duration deep voltage sags which can be compensated in very less interval of time with more efficiency an reliability. This circuit is cost effective and also having less weight as we didn't use any transformer. The circuit equations and working principle are given in theoretical analysis. Simulation results are presented in order to check the feasibility of the circuit for deep voltage sags. As DC link voltage adaptive method is used for fuzzified PB-AVQR circuit, the efficiency is also relatively high compared to other controller used circuits.

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