Introduction to a modern control system for DVR with minimize the losses

Hamzeh ali. Karami1, Asghar Taheri2, Mohammad Ali Fahim3

1- Zanjan Azad University / Faculty of Electrical and Computer, Zanjan, Iran.
Email: karamihamzehali@gmail.com (Hamzeh Ali Karami)
2- University of Zanjan / Faculty of Electrical and Computer Engineering, Zanjan, Iran.
Email: taheri@znu.ac.ir
3- Aluminum casting company Iran Khodro Abhar/ Zanjan, Iran.
Email: fahim.1975@yahoo.com

ABSTRACT:
Abstract: the losses in DVR has direct relationship to its performance i.e. there is no disturbance that it has been considered in the normal functioning of the network and in the presence of conflict (compensation time). A main determinant factor of the amount of losses after arrangement of power system which is related to control system. The control system is divided to two important parts: voltage references and switching patterns. the design of control system for DVR so to be performed while compensation of voltage sag, voltage swell, Harmonic voltage, limiting fault current and compensation of voltage unbalance has minimal loss and highest accuracy. In this paper, the loss in the proposed DVR and several samples of them through generation of the voltage references and different pattern switching are reviewed and compared. The simulation results of PSCAD/EMTDC software show the accuracy and speed of proposed DVR.

KEYWORDS: sag and swell voltage; voltage unbalance; control of voltage sensitive load; losses in DVR.

1. INTRODUCTION

the power quality since the late 1980’s for the power companies and subscribers has special significance for low and medium-voltage application, so that due to subscriber’s demand of power companies the percent of power quality improvement and specially voltage quality in distribution network has been more considered. Nowadays, one of the most concerns of power is the power quality problems for sensitive loads. According to daily increase of high number from these loads like computer, variable speed devices, phases logic controllers etc. often we need the High quality power supplies to use these equipment’s. Sag and swell voltage are very important phenomena of power quality that has very bad impact on sensitive loads and has been caused the greatest economic damage in all over the world [1], [2].

The voltage quality is one of the most important sector of power quality. The phenomena like voltage sag and swell has been caused disturbance in voltage network. Voltage sag is in short-reduction in effective value of the voltage. According to IEEE standard 1159-1995, sag voltage is called when the sudden decrease of effective voltage to the amount of 10-90% happens between 0.5 cycles to 1 minute. The short term increase in the effective value of the voltage is called swell which is according to standard IEEE 1159-1995 it is called the sudden increase of effective voltage to the amount of 110% -180% rating, happens between 0.5 cycles to 1 minute. The sages of short term voltage often have been caused by starting the motors and short circuits. The main factors of voltage swells of unequal errors are the exit of large loads and entering the large capacitor banks. Thus, the presence of these two phenomena (sag and swell voltage) will be caused to failure the sensitive loads. We can use various techniques based on power electronic for increase of power quality problems which is known as custom power. Dynamic voltage restorer (DVR) is one of the most important types of equipment's which is placed between sensitive loads and network in series and by injection of controlled dynamic voltage – controlled, despite of Disturbances in the power supply voltage, it has been provided to have a Sinusoidal voltage with preset amplitude and phase in two sensitive loads [3]. The Fig. 1 shows the components of a DVR.

The DVR does not operate in normal condition of network and only there is low conduction losses in inverter. In case of voltage sag and swell in the
distribution and so in the place of sensitive load, first, DVR identifies the sag and swell voltage and then it injects the required voltage to the network. So that the DC-link voltage is converted by voltage source inverter to alternating voltage. This alternating voltage can be in three voltages of single-phase AC or three voltages of three-phase AC that the voltage of each inverter phase is injected through injection transformer related to the same phase in series is injected to the voltage in the relevant load. Depending on the type of control system design, amplitude and phase of voltage injection of DVR is controlled that during the disturbance the desired amplitude and phase of voltage sensitive load is maintained [4]-[10].

![Fig. 1. The overall structure of a DVR in a single-phase circuit.](image)

Important discussion that about DVR can be stated is related to losses. Because, how much the amount of losses is low, then equally accuracy compensation will of DVR be higher. In this paper, the simulation of sample system with different control systems in low level voltage has been applied by using PSCAD/EMTDC software. The review of losses with 4 different control systems (the generation of voltage references and different pattern switching) has been done and the impact on performance of DVR has been indicated.

2. CONTROL SYSTEM OF DVR

The main function of control system of DVR is providing the suitable strategy of switching for keeping constant voltage in two heads of sensitive load. The design of a control system depends on the type of voltage compensation of sensitive load. For the performance of DVR against voltage disturbances, there are three known compensation strategies namely, minimum energy, pre-sag and minimal rating which is one of the strongest of them is minimum energy compensation strategy (in-phase). If the load is not sensitive to the varying of phase voltage, then we can change the phase difference between voltage source and load voltage so that reaches to desired value. This compensation strategy is called minimal rating or in-phase. In this compensation method, we can minimize voltage and the injected real power of DVR through changing the phase voltage load and thus changing phase voltage source [4], [10]. The Fig. 2 shows phases diagram source [4], [10]. The Fig. 2 shows phases diagram related to minimum energy strategy (in-phase).

![Fig. 2. Phases diagram related to minimal rating strategy [3].](image)

In this method, voltage injection by DVR in compensation period with the voltage after occurring error is in-phase. Therefore, in this method, only amplitude voltage is restored. The main benefits of this method are that to minimize the injection voltage by DVR. The amplitude and phase of injection voltage by using this method is calculated as follows [3], [10].

\[
V_{DVR} = |V_{inj}| \quad V_{inj} = |V_{pre-sag}| - |V_{sag}| \\
\angle V_{inj} = \theta_{inj} = \theta_{Sag}
\]

Where these relationships are \( V_{inj} \) injection voltage, \( V_{pre-sag} \) pre-sag voltage, \( V_{sag} \) sag voltage, \( \theta_{Sag} \) & \( \theta_{inj} \) pre-sag phase voltage and phase injection voltage respectively. In this case, during compensation of phase load voltage (\( \angle V_l \)) is equal to phase voltage source (\( \angle V_s \)). Due to current load passes from DVR, indeed setting the \( V_{DVR} \) is caused to set the \( S_{DVR} \) and thus, minimum \( S_{DVR} \) is achieved for minimum \( V_{DVR} \) [3].

There are different systems that generate the voltage references based on minimum energy strategy. Synchronous reference frame system (SRF) is one of the most famous of them that following the description of SRF system, we have been introduced the proposed system.

2.1. Synchronous reference frame [1], [7]

Fig. 3 shows the common control system of SRF that park transform is used for design of it. Park transform, actually converts phase network voltage to new coordinates. The basis of this transformation is following the instantaneous positive sequence angle (\( \theta = \omega t + \phi^* \)) through phase lock loop (PLL).

As can be seen in Fig. 3, synchronous reference frame system consists of two main parts. The upper part of compensation of positive sequence component and at the bottom of negative sequence component takes place. It is worth mentioning that control of zero sequence is also often done by connector Y/Δ of distribution.
In order to compensate the positive sequence component is necessary to convert instantaneous angle $+\theta$ is applied to transformation’s $dq$ and its reverse conversion. Thus, positive sequence component has been considered as a reference and negative sequence component is equal to two times of the frequency of fundamental component ($2f_0$) and in opposite direction of positive sequence component is rotating. In other words, $D_p$ & $Q_p$ in addition to constant values (DC), have oscillatory components so that to eliminate this problem, we should have been used the low pass filters. Through removing the oscillation, the parameters will be fixed so that the component $D_p$ corresponding to amplitude of voltage sag and component $Q_p$ nearly equals to zero. Now, through comparing the amplitude of sag to reference value and $Q_p$ with zero, then reference values of positive sequence are achieved so that instantaneous reference values will be obtained through applying it to reverse of transformation’s $dq$.

At the bottom also, the angle $-\theta$ has been applied to the blocks and reverse the above process takes place only the except is that the values of $D_p$ & $Q_p$ will have been compared to zero, so after compensating, there are not any negative sequence component. Finally, by sum of reference values obtained from two sections of control system, the final error signal will be achieved and it will be sent to create injection voltage to delta-sigma modulator.

**2.2. The proposed control system**

The system shown in Fig. 4, is the view of proposed system which has the duties such as detection event, Determining the operating mode (standby mode, compensate mode), Calculating a correction voltage, Modifying any interference with injection of voltage Series and finally returning DVR to normal mode after elimination of interference. The performance of system is that to enter the line voltage distribution ($V_{sa}, V_{sb}, V_{sc}$) to Phase lock loop (PLL) and is formed the output $\theta$. By multiplying this angle by a constant, new angle will be achieved (Convert degrees to radians) and thus, through sinus of this angle and its multiplying by reference values, phase voltage $a$ will be achieved so it should be equaled to $V_{sa}$ for the phases b and c this action has been repeated by shifting 240 and 120 degrees respectively and the obtained phases voltage, b and c which must be equaled to $V_{sb}$ & $V_{sc}$ the design of this system without requiring $dq$ theory, has simple structure that able to compensate the interferences of voltage such as: unbalance voltage, sag and swell of balance voltage, sag and swell of unbalance voltage. Also, we should be done the fault current limiting and removing the voltage harmonics at the source by this system.

![Proposed control strategy of generating the reference voltages for ΣΔ technique.](image)

After generating the reference voltages with SRF system or proposed system, perform the switching in further researches that has been used by patterns based on PWM modulation. Electromagnetic interference is a problem in this modulation so that has been caused bad impact on Information Telecommunications, electronic, etc and in general, it has been caused to failure the other sensitive loads that has not been used the DVR. In this paper, sigma-delta modulation has been offered for performing the switching. In the structure of this modulation has been used the integrator with suitable rate of gain. In fact, detection and removing the noise inside these loops has been performed and finally, by using this pattern in addition to compensate the disturbances voltage by DVR, there is not any problem for other sensitive loads.

**2.3. Sigma-delta modulation**

Due to in old modulations, especially in usual modulation, noise is distributed on frequency axis unevenly and we can use the low pass filter for smoothing some noises and harmonics. In delta-sigma modulation, the distribution of noise is different and some of them increases in high frequency band. Since, this noise has the frequency that is different from frequency of fundamental component of signal, as a consequence simply by using the low pass filter was removed and compare with old convertors has higher signal to noise ratio.

For sigma-delta modulation, we can design and build in different degrees. The Fig. 5 displaying the proposed modulation method that this structure, called the second order sigma-delta modulation. The second order sigma-delta modulation is very resistant to circuit under
unsuitable conditions and compared with the first order modulation has one more parameter and this parameter is related to gain of two way- closed loop. this is caused that such modulators could determine the Low-frequency characteristics of the circuit by external way and according this, system is more stable, also High-frequency components has been identified by inner loop. Additionally, we can compensate the delay of outer loop by increase the gain of inner loop [11]. Thus, the second order sigma-delta modulation with considering the complexity of circuit and signal to noise ratio is suitable option. Also, we can build the higher order sigma- delta modulation but the building of them is not simply adding one more order like converting the first order to the second order. Thus, the complexity of this method is in the phase rotation by more than two integrators so that can be caused the unstable system. As a consequence, we should be considered the especial conditions in design of these modulators, thus against the losses is a competitor factor.

One of the important parameters in design of sigma – delta modulation, is range of signal amplitudes, so that should be matched in output integrator. Thus, the signal in the first integrator has good range but in the second order has very wide range and so, this signal is cut almost about 4 times of input signal. Otherwise, the effect of identifier in modulation system is not visible. The signal after two steps of processing is entered to pulse generator system (Fig. 6) so that in this part of system in addition to calculate the fire pulses, it has been indicated to start the IGBT gates.

![Diagram](image1)

**Fig. 5.** The structure of the second order sigma-delta modulation for three-phase.

![Diagram](image2)

**Fig. 6.** Generator system of fire pulses for 6-pulse inverter.

In this paper we have been used the proposed control strategy for generating the reference voltage and sigma-delta modulator in the structure of control system proposed DVR. thus, we have been performed the simulations for review of performance DVR against voltage disturbances with proposed DVR but, the review of losses has been done by 4 different control systems. Because of the numerous number of figures and the goal has been followed, only the results of losses in both normal operation and compensation time for 4 control system has been brought.

3. THE RESULTS OF SIMULATION:

In order to see the performance of proposed DVR in compensating voltage disturbances, one sample network has been used in [1] with the Parameters listed in the Error! Reference source not found. has been simulated by PSCAD/EMTDC software. It is worth mentioning that the reviews in respect of losses, also has been performed by a power system with listed parameters in Error! Reference source not found. as well as different control systems.

**Table 1.** Network and DVR specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Voltage</td>
<td>380(V_{L-L}) (RMS)</td>
</tr>
<tr>
<td>Load</td>
<td>S</td>
</tr>
<tr>
<td>Cos (\phi)</td>
<td>0.88</td>
</tr>
<tr>
<td>Frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Tuned Filter</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>0.2 (\Omega)</td>
</tr>
<tr>
<td>L</td>
<td>6(mH)</td>
</tr>
<tr>
<td>C</td>
<td>45(uf)</td>
</tr>
<tr>
<td>Injection Transformer</td>
<td>0.3:0.45</td>
</tr>
<tr>
<td>DC Link Voltage</td>
<td>700(V)</td>
</tr>
</tbody>
</table>

3.1. Three phase to ground fault

Simulation is that the disturbances voltage has been occurred in next bus and its impact in PCC bus and finally the effect of voltage sag in bus is seen in loads that is feed from PCC bus. Placement DVR in the way of sensitive load could not lead to see the interferences voltage. Therefore, if DVR detects the event (voltage disturbances) by series injection voltage to the network, it will compensate the missing voltage. The Fig. 7 shows the voltage sag of three phase distribution \((V_{sa}, V_{sb}, V_{sc})\) with injection voltage of DVR \((V_{inj,a}, V_{inj,b}, V_{inj,c})\) and Sensitive load voltage compensation \((V_{La}, V_{Lb}, V_{Lc})\). This sag is created a reduction of 35\% in the voltage distribution that has been started from 1s and has been
3.2. Single phase to ground fault

Over 70% of recorded sags is in single phase to ground and the worst case is occurred when the system is not directly grounded, i.e. the system with an impedance is grounded. Since, in this case a voltage sag in one of the phases and two other phases’ voltage swell is occurred. Of course, in this part only single phase fault in system is reviewed that has been directly grounded. In this part assumes that a single phase to ground fault in next bus has been occurred and the impact on the PCC bus has been observed and finally has been caused the performance of DVR. The Fig. 8 shows the performance of proposed DVR under unbalance voltage sag (single phase fault).

3.3. Voltages swell of three phases

Voltage swell is an disturbances that like voltage sag is caused to failure the sensitive loads. Voltage swell with entering one large bank capacitors or exit of one large load in next buses leads to increase the voltage of PCC bus and finally, it has been caused to increase loads voltage that has connected to this bus. By placement the DVR in the way of sensitive load in addition to rapid identifying the voltage swell, exactly compensate the additional voltage. Fig. 9 shows a voltage swell of three phases in distribution \( (V_{sc}, V_{sb}, V_{sd}) \) with injection voltages of DVR \( (V_{inj,c}, V_{inj,b}, V_{inj,a}) \) and sensitive load voltage compensation \( (V_{Le}, V_{lb}, V_{La}) \). This swell has caused an increase of 130% in the voltages of distribution that has been started from 1s and has been continued for 100ms.

3.4. The review of losses

In this part, we review losses of inverter. Power dissipated due to Conduction losses and switching losses of the keys. The conduction losses of keys are function of the load, generating of references voltage and switching patterns of inverter. But, switching losses of inverter depend on circuit variables of dynamic. Total losses of switching Modules losses is calculated from (3), switching losses in inductive load from (4) and conduction losses from (5) [12], [13].

\[
P_{\text{Loss}} = P_{\text{Loss}_\text{sw}} + P_{\text{Loss}_\text{on}} \quad (3)
\]

\[
P_{\text{Loss}_\text{sw}} = \frac{1}{2} f_{SW} \times E_G \times I_G \times (t_{on} + t_{off}) \quad (4)
\]

\[
P_{\text{Loss}_\text{on}} = E_G \times I_G = R_{on} \times I_G^2 \quad (5)
\]
Where these equations $f_{sw}$, Switching frequency, $E_G$, maximum voltage of on key, $I_G$, current of switch, $t_{on}$, time delay on switch and $t_{off}$, time delay off switch. The proposed block diagram in Fig. 10 in fact, the calculations of related to (5) i.e. it has been done the conduction losses of inverter and so the reviews of this part, only related to conduction losses. The calculation of conduction losses is done by taking the absolute value of voltage and current of switch and passing them from low pass filter, the constant value of voltage and current will be achieved. By multiplying voltage by current, the amount of conduction losses will be achieved. So the losses of a IGBT has been calculated and by multiplying it by number of switches (6), total loss of inverter will be achieved. Conduction losses in inverter are the function of load, control strategy and switching pattern. Since, in all simulations the load has been assumed that it is fixed, thus, the review of conduction losses of inverter has been performed to generate the different references voltage and different switching patterns so that several samples of them has been simulated as follows.

![Fig. 10. The calculation of conduction losses in a 6-pulse inverter](image)

The cause of losses investigation can be considered in both normal operation and time of compensation. If generation system of references voltage (like SRF and proposed system and etc.) in normal performance is near to zero, then equally switching will be done and so the value of active power and injection voltages to the network in this case, are little that has been fed to the network and it will be caused to decrease the losses in normal performance of the network. If in normal operation, generated references voltage far from zero, then the reverse of above process will be repeated. The impact of above losses in normal operation in time compensation is more seen so that in the time of disturbances, compensation more than required value will be done. i.e. The calculation of correcting voltage is wrong and as a consequence, correcting the disturbances by injection voltage in series will not be done. Because of the numerous number of figures, only the figures related to proposed control system has been shown in Fig. 11 and Fig. 12. For four different control systems, the maximum values of losses noted in two operation mode has been described in Error! Reference source not found.

![Fig. 21. The conduction losses of DVR with generating of proposed references voltage, the proposed switching pattern in normal operation in network.](image)

![Fig. 32. The conduction losses of DVR with generating of references voltage, the proposed switching pattern in time of disturbances.](image)

<table>
<thead>
<tr>
<th>DVR Control System</th>
<th>Conduction Losses(MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Referenc e voltage</strong></td>
<td><strong>Switching pattern</strong></td>
</tr>
<tr>
<td>Proposed presented in Fig. 4</td>
<td>Sigma-delta modulation proposal presented in Fig. 5</td>
</tr>
</tbody>
</table>
due to the values obtained from simulation, the most conduction loss related to row 4 that is worst case in term of comparison and in the rows 2&3 the most losses has been seen. It has been concluded that from simulation of 4 control systems, according to Error! Reference source not found., is that the best case for decrease of losses has been applied by the proposed control system based on the proposed generating of references voltage and proposed sigma-delta modulation. It has been seen that the proposed generating of references voltage to dq theory with any type of switching modulation has the most impact on decrease of losses. Therefore, in design of control system, if the goal is the decrease of losses, then it should be considered the generating of referenced voltage and switching patterns. But if the aim is to minimize the losses for designer, the most impact on decrease of losses will be the selection of suitable switching.

4. CONCLUSION

In this paper, the introduction of different control systems in two parts namely as the generating of references voltage and switching patterns based on compensation in minimal rating strategy are discussed. Then, the modulation of proposed DVR in compensation of voltage sag and swell on a sample network in environment of PSCAD/EMTDC software is simulated and evaluated.

For the first time, the impact of losses on DVR in both normal and disturbances has been evaluated. It was expressed that after arrangement of power system and control system of DVR two parts namely as the generating of references voltage and switching pattern has the most impact on the decrease of loss. Thus, the simulation of DVR with 4 different control systems is performed. The results obtained from these simulations with 4 control systems in the part of generating of references voltage (SRF and proposed system) and in part of switching pattern (SPWM and sigma-delta modulation) are shown that the proposed control system has least loss. If the referenced voltage is near to zero, then equally switching as a consequence conduction losses will be less and the result will be the rapid detection of event and the exact calculation of missing voltage in time of compensation.

REFERENCES


