

A Novel Approach of Inverter Topology of DVR for Mitigation of Voltage Sags and Voltage Swells

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Abstract

Power quality problems have been attracting the eye of researches for decade. The presence of voltage disturbances at the point of common coupling (PCC) results in malfunction of sensitive industrial instruments, which turns out to be grid part failures, such as transformers, and economical losses. Modern electronic equipment and devices, such as microprocessors, microcontrollers, telecommunications equipment and sensitive computerized equipment etc. are susceptible to PQ problems. There are many different methods to mitigate voltage sags and swells, but the use of a custom power device is considered to be the most efficient method, e.g. FACTS for transmission systems which improve the power transfer capabilities and stability margins. The term custom power pertains to the use of power electronics controller in a distribution system, especially to deal with various power quality problems. To handle these situations, custom power apparatuses are utilized. Sensitive load has a severe impact on itself due to voltage sag and swell. Dynamic Voltage Restorer (DVR) is a power custom device used in power distribution network. Fuzzy Logic Controller Fuzzy logic (FL) controller is the heart of fuzzy set theory the major features are the use of linguistic variables rather than numerical variables. This control technique relies on human capability to understand the systems behavior and is based on quality control rules. Fuzzy Logic provides a simple way to arrive at a definite conclusion based upon vague, imprecise, noisy, ambiguous, or missing input information.

Keywords: Power Quality PQ , Point of Common Coupling (PCC), Dynamic Voltage Restorer (DVR) , Fuzzy Logic Controller Fuzzy logic (FL)

INTRODUCTION

Power quality issues are an issue that is becoming increasingly important to electricity consumers at all levels of usage. Power Quality related issues are of most distress because of the extensive use of electronic equipment. In arrears to this, various Power Quality issues arises like voltage sag or dip, very short and long interruptions, voltage spike, voltage swells, harmonic distortion, voltage fluctuation, noise, voltage unbalance and altered our power system. Power quality problems have been attracting the eye of researches for decade. The presence of voltage disturbances at the point of common coupling (PCC) results in malfunction of sensitive industrial instruments, that turn out to be grid part failures,

such as transformers, and economical losses. FACTS devices are the possible answer to shield sensitive loads against the most significant voltage disturbances, voltage harmonics, imbalance and sags. Definition of power quality may vary from person to person because we cannot define what power quality we only define what good is or bad power quality is as we can see that two identical devices or pieces of equipment might react differently to the same power quality parameters due to differences in their manufacturing or component tolerance. According to institute of Electrical and Electronic Engineers (IEEE) Standard power quality is defined as a, “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment”. The focus of this survey is on the use of FACTS devices in mitigation of Power Quality problems.

Electric power quality (Power Quality) has become the concern of utilities, end users, manufacturers, and all other customers. Power quality is the set of parameters defining the properties of power supply delivered to the users in normal operating conditions in terms of continuity of supply and characteristics of voltage (magnitude, frequency, symmetry, waveform etc.). Modern electronic equipment and devices, such as microprocessors, microcontrollers, telecommunications equipment and sensitive computerized equipment etc. are susceptible to Power Quality problems. Poor Power Quality has become a more important concern of both power suppliers and customers.

Application of deregulation policy in power systems results in growing attention regarding power quality issues. Although much efforts and investments are done by utilities to prevent power interruptions, it is not possible to completely control disturbances on the supply system. Many disturbances are due to normal operations such as switching loads and capacitors or faults and opening of circuit breakers to clear faults. Faults are usually caused by events outside the utility's control. These events include acts of nature such as lightning, birds flying close to power lines and getting electrocuted, and accidental acts such as trees or equipment contacting power lines.

A large number of disturbances generated by customer owned equipment and plant operations are beyond the utility's control. In industrial and commercial facilities, disturbances may be caused by the operation of arc welders and the switching of power factor capacitors and inductive loads such as motors, transformers, and lighting ballast solenoids. Moreover, fluorescent lamps, CFLs, and other devices that use power electronics such as switch-mode power supplies, television sets, light dimmers, and adjustable-speed drives can

also inject harmonics into the power system. Hence reliable power is essential for both utilities and customers.

Power Quality problem is “Any power problem manifested in voltage, current, or frequency deviations those results in failure or disoperation of customer equipment’s”. Power systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency.

A new design which incorporates a superconducting magnetic energy storage module as a DC voltage source to mitigate voltage sags and enhances power quality of a distribution system based on DVR. The dynamic voltage restorer (DVR) has become popular as a cost effective solution for the protection of sensitive loads from voltage sags and swell. There is a need for dynamical adjustment of the size of the neural network to effectively search for the minimum estimation errors of the measured signal.

MITIGATION OF POWER QUALITY PROBLEMS

DVR is a Custom Power Device used to eliminate supply side voltage disturbances. DVR is also known as Static Series Compensator which maintains the load voltage at a desired magnitude and phase by compensating the voltage sags/swells and voltage unbalances presented at the point of common coupling.

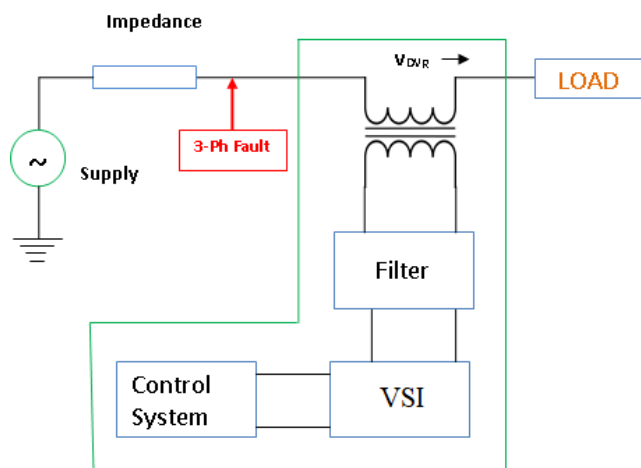


Figure 1. Schematic diagram of a Dynamic Voltage Restorer

- I) Injection/ Booster Transformer-The Injection / Booster transformer is a specially designed transformer that attempts to limit the coupling noise and transmit energy from the primary side to the secondary side. Its main tasks are, connects the DVR to the distribution network via the HV-windings of transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the Injection / Booster transformer serves the purpose of isolating the load from the system (VSC and control mechanism).

- II) Harmonic Filter-The main task of harmonic filter is to keep the harmonic voltage content generated by the VSC to the permissible level.
- III) Storage Devices-Batteries, flywheels or SMES can be used to provide real power for compensation. Compensation using real power is essential when large voltage sag occurs.
- IV) Voltage Source Converter-A VSC is a power electronic system consists of a storage device and switching devices which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. In the DVR application, the VSC is used to temporarily replace the supply voltage or to generate the part of the supply voltage which is missing.
- V) DC Charging Circuit-The DC Charging Circuit has two main tasks.(a)The first task is to charge the energy source after a sag compensation event.(b)The second task is to maintain dc link voltage at the nominal dc link voltage
- VI) Control and Protection-The control mechanism of the general configuration typically consists of hardware with programmable logic. All protective functions of the DVR should be implemented in the software. Differential current protection of the transformer, or short circuit current on the customer load side are only two examples of many protection functions possibility.

CONTROL SCHEME OF DVR

[7]The major objective of the control strategy is to ensure that the load bus voltages remain balanced and sinusoidal (positive sequence). Since the load is assumed to be balanced and linear, the load currents will also remain balanced (positive sequence) and sinusoidal. An additional objective is to ensure that the source current remains in phase with the fundamental frequency component of the PCC voltage. This requires that the reactive power of the load is met by the DVR.

The error e and change of error e_c are used as numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as [17]: negative big (NB), negative medium (NM), negative small (NS), zero (ZE), and positive small (PS), positive medium (PM), and positive big (PB). To ensure the sensitivity and robustness of the controller, the membership function of the fuzzy sets for $e(K), e_c(K), \Delta K_p$ and ΔK_i in this thesis are acquired from the ranges of $e, e_c, \Delta K_p$ and ΔK_i , which are obtained from thesis and experience. And the membership functions are shown in Fig.5.10.

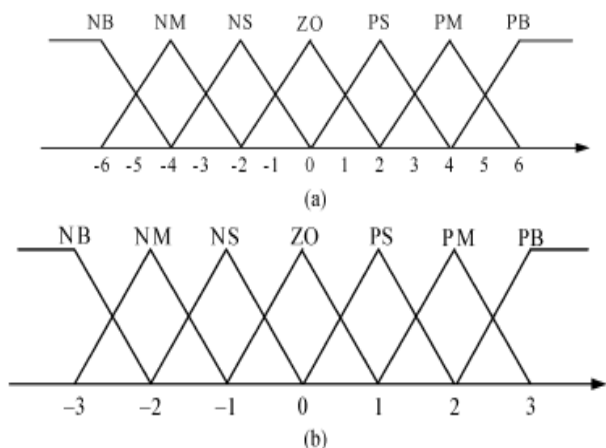


Figure 2. Membership functions of the fuzzy variable. (a) Membership function of ΔK_p and ΔK_i (b) Membership function of $e(K)$ and $e_c(K)$

For designing the control rule base for tuning ΔK_p and ΔK_i the following important factors have been taken into account.

- For large values of error $|e|$, a large ΔK_p is required, and for small values of error $|e|$, a small ΔK_p is required.
- For $e - e_c > 0$, a large ΔK_p is required, and for $e - e_c < 0$, a small ΔK_p is required.
- For large values of $|e|$ and $|e_c|$, ΔK_i is set to zero, which can avoid control saturation.
- For small values of $|e|$, ΔK_i is effective, and ΔK_i is larger when $|e|$ is smaller, which is better to decrease the steady-state error. So the tuning rules of ΔK_p and ΔK_i can be obtained as Tables.

Table 1: Adjusting rule of the ΔK_p

| ΔK_p | | e_c | | | | | | |
|--------------|----|-------|----|----|----|----|----|----|
| | | NB | NM | NS | 0 | PS | PM | PB |
| e | NB | PB | PB | PB | PM | PM | PS | 0 |
| | NM | PB | PB | PM | PM | PS | 0 | NS |
| | NS | PM | PM | PS | PS | 0 | NS | NM |
| | 0 | PM | PS | PS | 0 | NS | NM | NM |
| | PS | PS | PS | 0 | NS | NS | NM | NM |
| | PM | PS | 0 | NS | NM | NM | NM | NB |
| | PB | 0 | NS | NS | NM | NM | NB | NB |

Table 2: Adjusting rule of the ΔK_i

| ΔK_i | | e_c | | | | | | |
|--------------|----|-------|----|----|----|----|----|----|
| | | NB | NM | NS | 0 | PS | PM | PB |
| e | NB | 0 | 0 | NB | NM | NM | 0 | 0 |
| | NM | 0 | 0 | NM | NM | NS | 0 | 0 |
| | NS | 0 | 0 | NS | NS | 0 | 0 | 0 |
| | 0 | 0 | 0 | NS | 0 | PS | 0 | 0 |
| | PS | 0 | 0 | 0 | PS | PS | 0 | 0 |
| | PM | 0 | 0 | PS | PM | PM | 0 | 0 |
| | PB | 0 | 0 | PS | PM | PB | 0 | 0 |

The switching frequency of hysteresis control method with constant band width is high. This will make the system loss considerable. In order to produce a five level voltage at the converters output, to reduce the switching losses and to improve the behavior of DVR, fuzzy controller method is utilized. The fuzzy controller has two inputs: (i) The difference between the injected voltage and the reference voltage. (ii) The derivation of the error.

Considering the difference between converter output voltage and reference voltage and its derivation, the controller determines the voltage condition and directly commands the switches to turn on or off. In conventional hysteresis voltage control, switching signals are determined when the error reaches to upper or lower hysteresis band but as it is shown in Fig.3 in this new proposed method, switching commands are determined according to the error and derivation of the error. Fig 3 shows inputs and output membership functions. The definition of the spread of each partition, or conversely the width and symmetry of the membership functions, is generally a compromise between dynamic and steady-state accuracy.

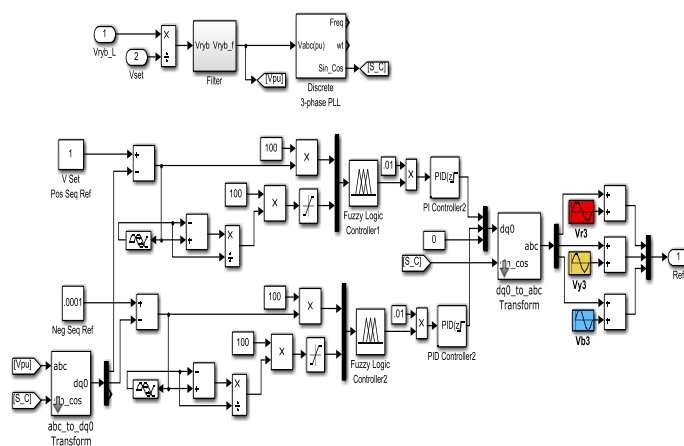


Figure 3. Control structure of DVR

The main considerations for the control system of a DVR include detection of the start and finish of the sag, voltage reference generation, transient and steady-state control of the injected voltage, and protection of the system.

SIMULATION CIRCUIT

Power quality problems are usually occurs due to switching on and switching off of loads and nonlinear loads. Sag occurs when there is increase in load or during the occurrence of load, a swell occurs when there is a sudden removal of load. This sag or swell in load voltage is sensed and its magnitude is compared with a reference voltage and the error signal is given to the PI controller. The output of error detector is feedback voltage minus input or reference voltage = $V_{in} - V_{ref}$

The difference between load voltage V_{in} and reference voltage V_{ref} is supplied to the PI controller. The PI controller voltage is taken as feedback.

The fuzzy based PI controller is the most frequently used controller in the DVRs. The disadvantage of the PI Controller is its inability to work well under a wider range of operating conditions. Hence fuzzy based PI controller is proposed. In this control method, PLL for each phase tracks the phase of network voltage phasor and generates a reference signal with magnitude of unit to supply frequency for each phase.

It is because, the phase of the supply voltage prior to the sag is generally preferred and if the PLL reacts quickly to changes in the phase during sag, the post-sag phase may be used. Conventionally, once sag is detected, the target phase of the voltage reference is fixed to the pre-sag phase to ensure that if the reference is correctly tracked, then the load voltage phase will remain unaffected. There are three distinguishing methods to inject DVR compensating voltage, that is, pre-sag compensation method, in-phase compensation method, and minimal energy method. In this thesis, the adopted control strategy is pre-sag compensation to maintain load voltage at pre fault value. The simulation diagrams of closed loop system for voltage sag and swell is as shown below.

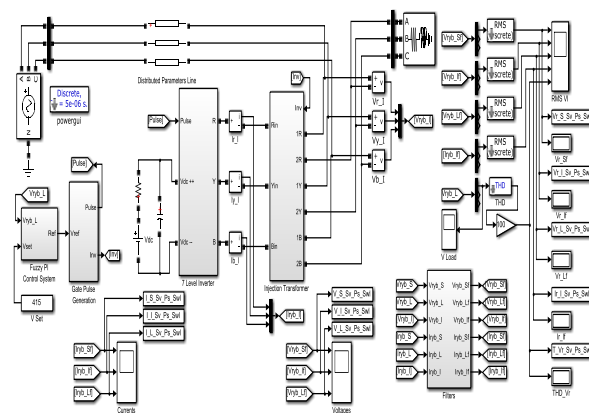


Figure 4. Simulation diagram – Dynamic Voltage Restorer

Dynamic Voltage Restorer (DVR), which is one of the most efficient and effective modern custom power devices, used in power distribution networks. A new control algorithm for the DVR is proposed in this thesis to regulate the load terminal

voltage during sag, swell in the voltage at the point of common coupling (PCC).

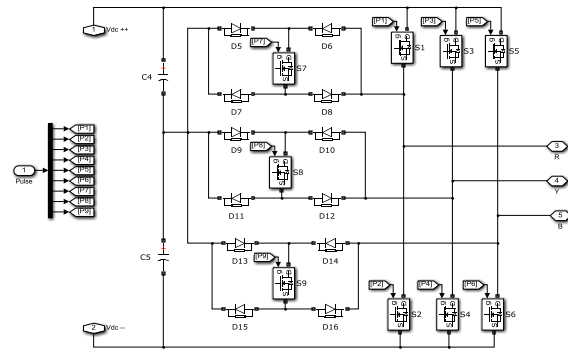


Figure 5. Seven-level converter based DVR system

These voltages, when injected in series with a distribution feeder by a voltage source inverter (VSI) with (a) case 1 SPWM control, (b) case 2 third order injected SPWM and (c) case 3 third order injected phase shift SPWM can regulate the voltage at the load terminals against any power quality problem in the source side. It first analyzes the power circuit of the system in order to come up with appropriate control limitations and control targets for the compensation voltage control through the DVR. The various advantages of multi-level inverter are, they can generate output voltages with extremely low distortion and lower dv/dt, they draw input current with very low distortion, they generate smaller common-mode (cm) voltage, thus reducing the stress in the motor bearings, they can operate with a lower switching frequency.

Table 3. Switching states for seven level inverter

| Time Slot | Switches | | | | | | | | |
|-----------|----------|----|----|----|----|----|----|----|----|
| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
| T1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 |
| T2 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| T3 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 |
| T4 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 |
| T5 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| T6 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| T7 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 |
| T8 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| T9 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| T10 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 |
| T11 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| T12 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 |

Table 4 summarizes the specification of the simulation of the DVR

Table 4: Specification of the simulation of the DVR

| S. No. | Parameter | Values |
|--------|--------------------------------|-------------|
| 1 | Main Supply Voltage | 425V |
| 2 | Series Transformer turns ratio | 1:1 |
| 3 | DC Bus Voltage | 530V |
| 4 | Filter Capacitance | 10 μ F |
| 5 | Filter Inductance | 7mH |
| 6 | Line Frequency | 50Hz |
| 7 | Line Inductance | 1mH |
| 8 | Line Resistance | 0.01 ohm |
| 9 | Capacitance | 80 μ F |
| 10 | Load Voltage | 425V |
| 11 | Load Resistance | 20 Ω |
| 12 | Load Inductance | 30mH |

ANALYSIS OF SIMULATION RESULTS

The control of the DVR is implemented through derived reference load terminal voltages. The multi-level scheme is simple to design. Simulation results carried out by MATLAB with its Simulink and Sim Power System (SPS) tool boxes to verify the performance of the multi-level method.

Case 1: Mitigation of Power Quality problems by DVR with SPWM

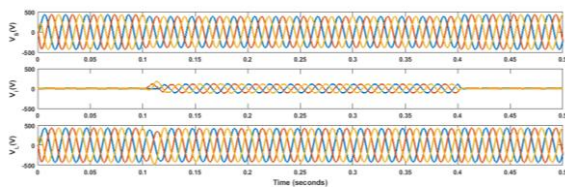


Figure 6. DVR with SPWM for Sag(10%) Voltage

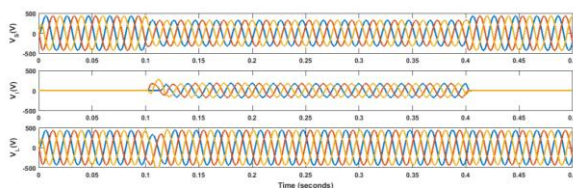


Figure 7. DVR with SPWM for Sag (25%) Voltage

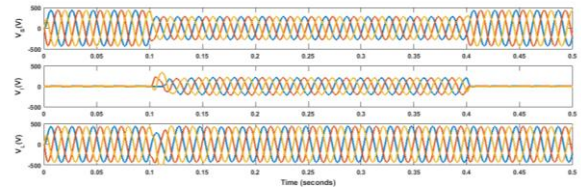


Figure 8. DVR with SPWM for Sag(35%) Voltage

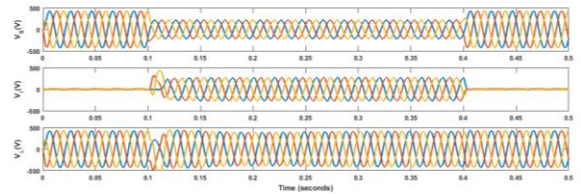


Figure 9. DVR with SPWM for Sag(50%) Voltage

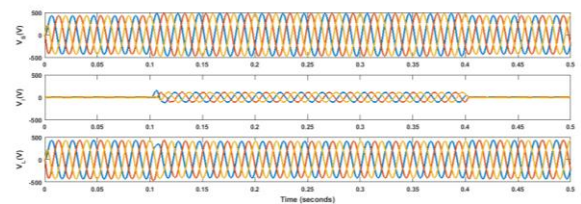


Figure 10. DVR with SPWM for SWELL

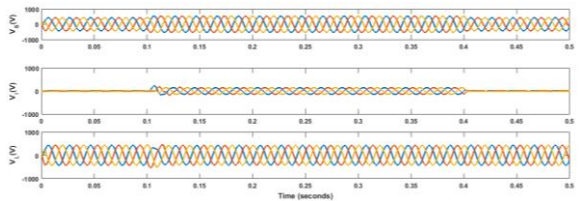


Figure 11. DVR with SPWM for SWELL (25%) Voltage

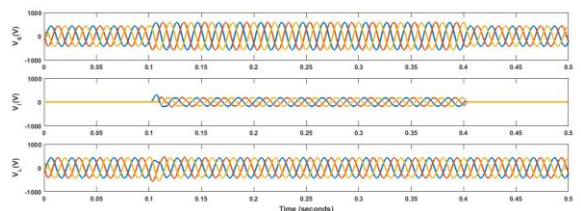


Figure 12. DVR with SPWM for SWELL (35%) Voltage

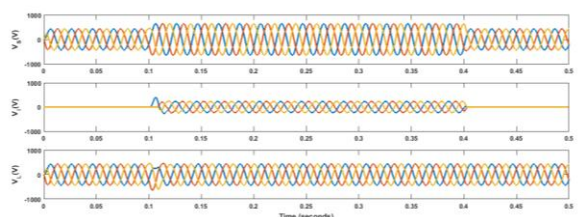


Figure 13. DVR with SPWM for SWELL(50%) Voltage

Case 2 : Mitigation of Power Quality problems by DVR with third order injected SPWM

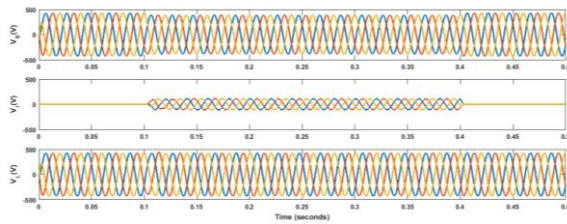


Figure 14. DVR with THIRD ORDER HARMONICS INJECTED SPWM for Sag(10%) Voltage

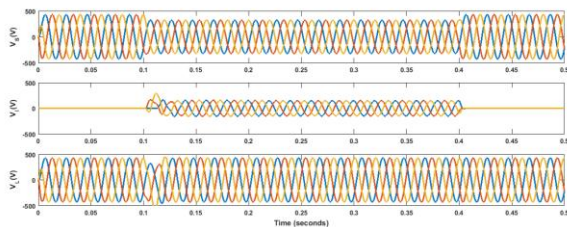


Figure 15. DVR with THIRD ORDER HARMONICS INJECTED SPWM for Sag(25%) Voltage

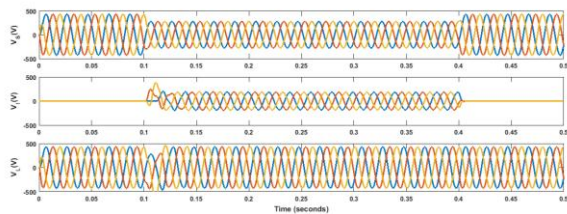


Figure 16. DVR with THIRD ORDER HARMONICS INJECTED SPWM for Sag(35%) Voltage

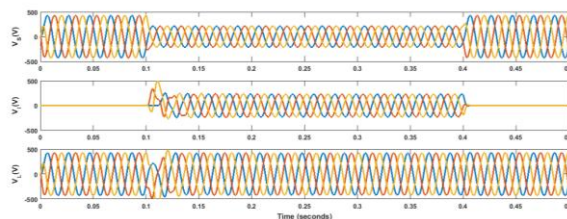


Figure 17. DVR with THIRD ORDER HARMONICS INJECTED SPWM for Sag(50%) Voltage

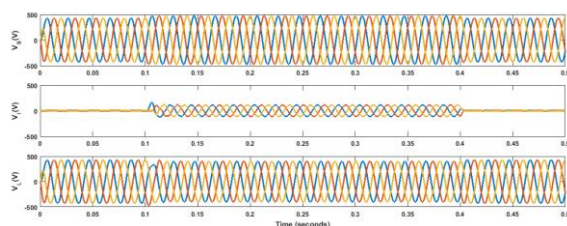


Figure 18. DVR with THIRD ORDER HARMONICS INJECTED SPWM for SWELL 10%) Voltage

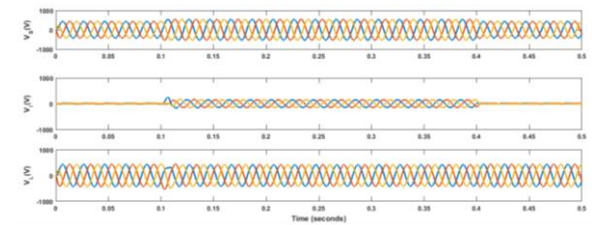


Figure 19. DVR with THIRD ORDER HARMONICS INJECTED SPWM for SWELL (25%) Voltage

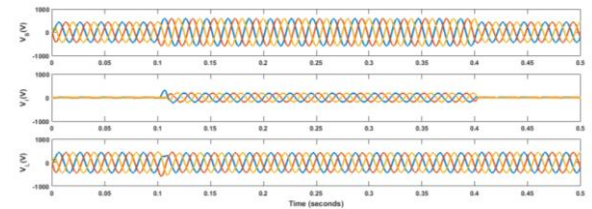


Figure 20. DVR with THIRD ORDER HARMONICS INJECTED SPWM for SWELL (35%) Voltage

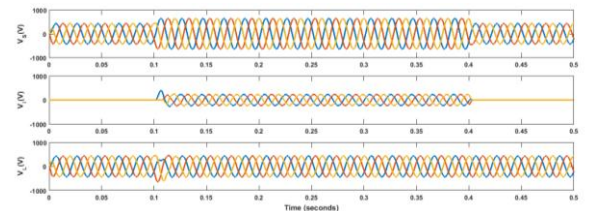


Figure 21. DVR with THIRD ORDER HARMONICS INJECTED SPWM for SWELL (50%) Voltage

Case 3: Mitigation of Power Quality problems by DVR with third order injected phase shift SPWM

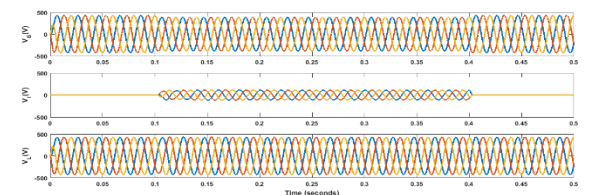


Figure 22. DVR with THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM for Sag (10%) Voltage

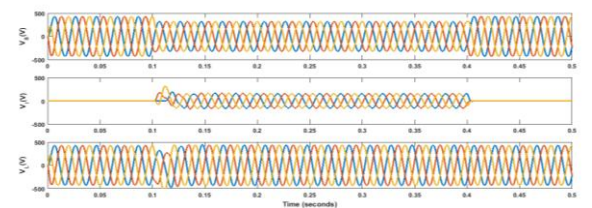


Figure 23. DVR with Third Order Harmonics Injected Phase Shift SPWM for Sag (25%) Voltage

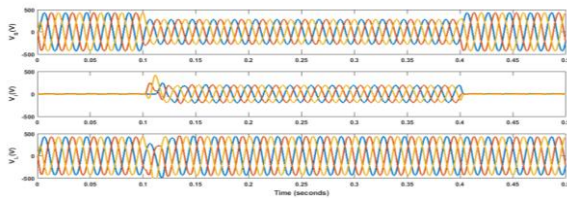


Figure 24. DVR with THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM for Sag(35%) Voltage

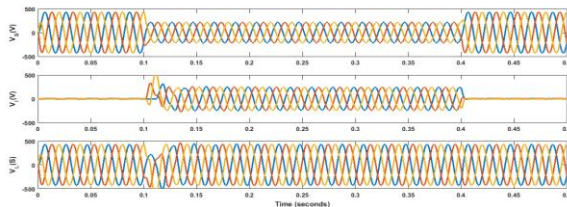


Figure 25. DVR with THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM for Sag(50%) Voltage

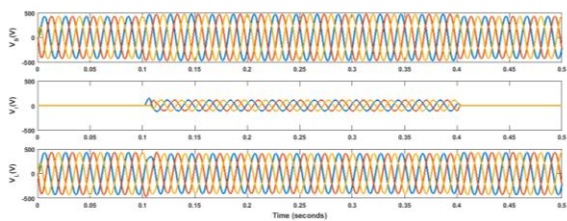


Figure 26. DVR with THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM for SWELL 10%) Voltage

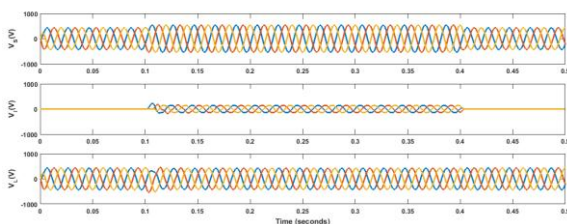


Figure 27. DVR with THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM for SWELL (25%) Voltage

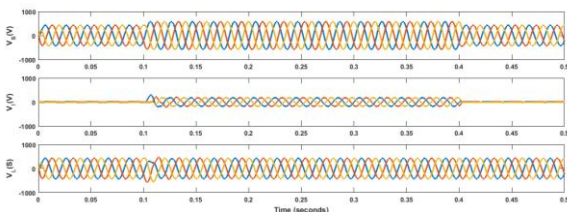


Figure 28. DVR with THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM for SWELL (35%) Voltage

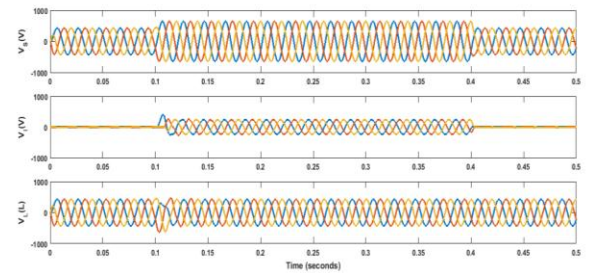


Figure 29. DVR with THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM for SWELL (50%) Voltage

- Above waveforms shows voltage sag/swell initiated at 0.1sec and it is continued up to 0.4sec with duration of 0.3sec.
- Injected voltage is originated at 0.1 sec and it is continued up to 0.4sec with a duration of 0.3sec,
- So the load voltage from 0.025sec to 0.5sec voltage level is maintained at 415V

SUMMARY OF THE SIMULATION RESULTS

| | | VOLTAGE | | | |
|---|-----|---------|----------|--------|------|
| | | SOURCE | INJECTED | LOAD | THD |
| SPWM | 10% | 387.07 | 109.88 | 423.84 | 1.34 |
| | 25% | 322.58 | 167.72 | 424.40 | 2.6 |
| | 35% | 279.59 | 204.07 | 424.68 | 3.4 |
| | 50% | 215.10 | 266.29 | 422.42 | 4.73 |
| THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM | 10% | 387.07 | 111.30 | 427.51 | 0.63 |
| | 25% | 322.58 | 155.42 | 425.82 | 1.06 |
| | 35% | 279.59 | 190.21 | 426.52 | 1.32 |
| | 50% | 215.10 | 240.56 | 425.96 | 1.74 |
| THIRD ORDER HARMONICS INJECTED SPWM | 10% | 387.07 | 106.84 | 428.36 | 0.86 |
| | 25% | 322.58 | 148.49 | 426.10 | 1.42 |
| | 35% | 279.59 | 181.30 | 426.24 | 1.79 |
| | 50% | 215.10 | 229.67 | 423.27 | 2.37 |

| SWELL | | VOLTAGE | | | |
|---|-----|---------|----------|--------|------|
| | | SOURCE | INJECTED | LOAD | THD |
| SPWM | 10% | 473.05 | 108.57 | 423.27 | 0.23 |
| | 25% | 537.68 | 146.09 | 421.71 | 0.74 |
| | 35% | 580.67 | 178.47 | 424.40 | 1.17 |
| | 50% | 645.16 | 229.10 | 426.81 | 1.85 |
| THIRD ORDER HARMONICS INJECTED PHASE SHIFT SPWM | 10% | 473.05 | 108.89 | 423.27 | 0.22 |
| | 25% | 537.68 | 147.22 | 423.13 | 0.69 |
| | 35% | 580.67 | 179.46 | 427.09 | 1.14 |
| | 50% | 645.16 | 235.61 | 427.80 | 1.9 |
| THIRD ORDER HARMONICS INJECTED SPWM | 10% | 473.05 | 113.01 | 422.42 | 0.47 |
| | 25% | 537.68 | 150.47 | 421.71 | 1.91 |
| | 35% | 580.67 | 185.68 | 422.99 | 3.13 |
| | 50% | 645.16 | 228.96 | 425.25 | 4.2 |

CONCLUSIONS

In this paper power quality problems mitigation algorithm is proposed which is compared and implemented by using MATLAB/SIMULINK algorithms.

The identification process is very accurate which includes duration and depth of the power quality problems. Different conditions were considered and fault detection was done. When fault occurs in all phases, individually and with combinations of two phases mitigation is done. In this thesis an overview of multi-level DVR is presented. DVR is an effective custom power device for voltage sags and swells mitigation through simulation.

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