17th International Conference on Renewable Energies and Power Quality(ICREPQ'19)
Tenerife, Spain, 10th to 12th April, 2019
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.17, July 2019

FACTS Family for Voltage Sag Alleviation: Performance Study and Analysis

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Abstract. Voltage sag is one of the most considerable problems in power distribution system. In this work the performance study of the FACTS family; i.e. the distributed compensator (D-STATCOM), dynamic voltage restorer (DVR), and pulse width modulation (PWM) switched auto-transformer, is carried out, with regard to the number of switching devices and the valid compensating capability in comparison to the generally known compensators. Each of the aforementioned FACTS devices is investigated and analyzed. The proposed control schemes used to control these devices are simulated by using MATLAB/Simulink software. Comparative analysis based on the implementation of these devices in compensating voltage sag is presented in this study. The main contribution of this work is the study and analysis of the behavior of FACTS family in reducing the voltage imbalance, the selection of the device most suitable to the application and also the control of the device such that desired performance can be achieved such that the power quality of the distribution networks is effectively improved.

Key words

FACTS family; voltage quality improvement; D-STATCOM; DVR; PWM switched auto-transformer; sag compensation.

1. Introduction

Nowadays, power quality (PQ) enhancement is affecting many issues occurred in the electric transmission and distribution systems; e.g., harmonics, frequency variations, transients and voltage variations, etc. System PQ delivered to the end-user is very important since the performance of the consumer's tools is heavily dependent on it. The operations of most of the loads depend extremely on the voltage level of the power being supplied to them. However, in the electric power system there are deviations in the voltage and frequency levels due to the faults, sudden switching operations, etc.

Among the disturbance troubles, voltage sag is considered as one of the most severe troubles to the industrial equipment and the most dangerous problem of power quality, which affects the utility grid broadly [1]. A voltage sag is recognized as the variation of the RMS voltage level from 0.1 to 0.9 pu of the nominal voltage at a point of electrical system. The disturbance induced by the voltage sag is generally characterized by the retained voltage magnitude, duration and phase angle jump. The magnitude of voltage sag at a specific point depends on the system configuration, fault type, fault impedance and fault distance from the point of consideration. The duration of sag is the time at which the voltage is below the threshold value, which is determined by the fault clearing time. In a 3-phase system all the RMS voltages should be considered for calculating the duration of the sag. A sag starts when one of the phase RMS voltages is less than the threshold and continues until all the 3-phase voltages are recovered above the threshold value. The short circuits in electric power system not only cause a sag in voltage, but also change system phase angle (phase angle jump), which causes the shift in zero crossing of the instantaneous voltage and affects the power electronic converters that use phase angle information for their firing. The major sources of voltage sag are caused by faults in the power system, starting of electric motors which draw more current and other load variations connected to the system [2].

With the improvement in the power electronics family, there are different technical solutions for reducing the above problems existing in the power system [3-4]. The FACTS devices are most suitable to keep the voltage in a standard level at the point of common coupling (PCC). The insertion of FACTS devices in the power system can help in improving the reliability and increasing the power quality. Different compensation techniques are available, in which the use of FACTS devices is the most effective and economic solution [5].

In this work, the performance study of the FACTS devices for the compensation of voltage imbalance is carried out and the control unit based on the RMS voltage is used to identify the sag disturbances [6]. The compensation of voltage sag based on the D-STATCOM, DVR, and PWM switched auto-transformer is studied and analyzed. The last compensator results in less switching devices (one switching device per phase), reduced gate drive circuit size, and without energy storage device. In this research, simulations of the voltage sag compensators are performed by using

Matlab/Simulink software and the performance results are presented and analyzed. The paper is organized as follows: Sections 2, 3 and 4 give the description of the D-STATCOM, DVR, and proposed PWM switched auto-transformer systems, and the corresponding control schemes. The simulation results are given and discussed in the section 5. Finally, some conclusions are drawn.

2. Description of distributed compensator system

D-STATCOM is a power electronic based device that protects the distribution bus from voltage variations, which is generally three-phase and inserted in parallel to the distribution bus at the PCC. D-STATCOM is used to stabilize the voltage of utility grid, to increase the transmission capacity, and also to make the compensation of harmonics, reactive power, power factor correction, and voltage regulation [7].

A. General construction

D-STATCOM is specially designed to regulate the voltage bus-bar either by generating or absorbing the reactive power. Essentially, it consists of a two-level voltage source converter (VSC), a DC energy storage device and a magnetic coupling inserted in shunt to the distribution system.

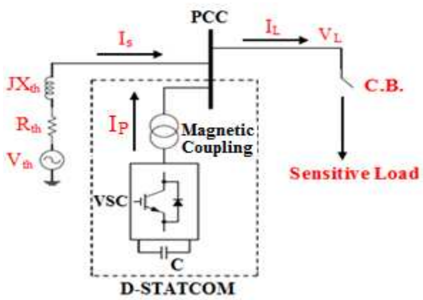

Fig. 1: Configuration of distributed compensator

The VSC inserted in parallel to the distribution grid provides different features topology; e.g. the reduction of current harmonics, the improvement of power factor, and the compensation of voltage sag and reactive power. The main purpose of VSC is to generate sinusoidal voltage by taking the input from the charged capacitor. This voltage is known to the system through the reactance of the magnetic coupling. Usually, it uses PWM switching scheme for this target. The voltage variation towards the reactor is used to produce the real and reactive power exchange between the D-STATCOM and transmission network, and thus can improve the system performance [8-9].

B. Operation principle

The main principle of a distributed compensator in voltage sag compensation is to regulate the bus voltage magnitude by dynamically generating or absorbing the reactive power to the AC system. D-STATCOM can operate either as an inductor or as a capacity depending on the value of bus voltage. The AC terminal voltage is equal to the sum of the inverter rated voltage and the voltage across the reactive of magnetic coupling in both modes of operation [10].

C. Control scheme

The main task of the distributed static compensator control scheme for voltage compensation is to control the amount of reactive power exchanged between the supply bus and distributed compensator. When the PCC voltage is lower than the rated value, D-STATCOM generates reactive power, while the PCC voltage is higher than the rated value, D-STATCOM absorbs reactive power. In order to achieve the desired features, the firing pulses to PWM-VSC are controlled. The real bus voltage is compared with the reference (rated) value and the error is passed across a PI controller, which creates a signal as input to the PWM generator to produce triggering pulses such that the voltage imbalance is corrected.

3. Description of dynamic voltage restorer system

DVR is a power electronic based device that protects critical loads from the voltage imbalance and is an arrangement associated custom power device. It is connected in series with the sensitive load and can absorb active and reactive power from the utility grid for compensating the load voltage harmonics, and thus improving the system power quality and providing the active power required by the load under system frequency variations. The device works through inserting an uncontrolled rectifier at the input of the VSI and can protect the system against any other voltage imbalance that occur in the power system [11].

A. General construction

The DVR unit is a series connected device used to inject voltage of required magnitude and frequency. The basic configuration of a DVR is depicted in Fig. 2 and the DVR main components are described in [2, 3].

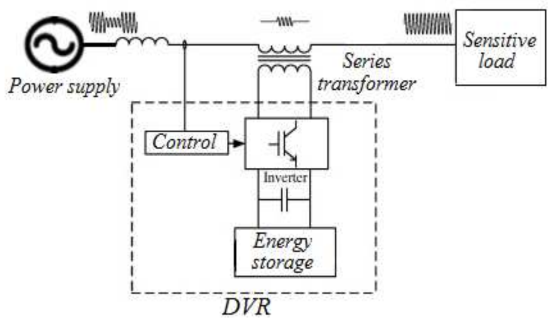

Fig. 2: Typical Configuration of DVR

Voltage source inverter (VSI): The VSI is composed of solid state switches such as IGBT's or GTO's to convert the DC input to AC and also to inject the AC voltage for compensating the decrease in the supply voltage. The switches of the VSI are operated with the PWM technique to generate the voltage of required magnitude and frequency.

Energy storage devices: The storage unit consists of batteries, capacitors, and super magnetic energy storage (SMES). For DVR with internal storage capacity, energy is taken from the faulted grid supply during the sag. Here a rectifier is used to convert the AC voltage from the utility grid to DC voltage required by the VSI.

Filter unit: An LC filter is inserted at the output of the VSI to filter the harmonics existing in the output voltage of VSI and to reduce the dv/dt effect on the windings of the transformer.

Insertion transformer: It is used to insert the DVR with the distribution feeder. In case of 3-phase system, 3-

single phase transformers are used to connect the DVR with the power grid.

B. Operation principle

The main working principle of the DVR is to inject voltage of required magnitude and frequency that is desired by the power grid. At normal operation, DVR will be in stand-by mode. During the period of disturbances in the system, the rated voltage is compared with the voltage variation and the DVR injects the difference voltage that is required by the load.

C. Control scheme

The principle meditations for the DVR control are the identification of the initiate and fulfillment of the hang, voltage reference time, transient and unfaltering state control of the infused voltage and security of the system [11]. The basic concept behind the control system is to find the amount by which the supply voltage is dropped. The 3-phase supply voltage is compared with the reference voltage. If there is voltage sag then an error occurs, and the error voltage is sent to the PWM generator to provide the firing pulses to the switches of the VSI such that required voltage is generated. The entire control unit can be implemented in 2-ϕ rotating (d-q) coordinate system.

4. Description of PWM auto-transformer system

An auto-transformer has higher efficiency as compared to the two-winding transformer because it is of small volume and requires less conductor material in its construction. This device can be used for compensating voltage sag by boosting supply voltage in distribution network.

A. General construction

The basic configuration of an auto-transformer used in voltage sag compensation has the secondary voltage higher than the primary voltage and the transformer works as a step-up transformer.

B. Operation principle

The proposed circuit for voltage sag compensating consists of a PWM switched power electronic device inserted to an auto-transformer in series with the load as depicted in Fig. 3. The auto-transformer is controlled logically by a PWM power electronic switch [12].

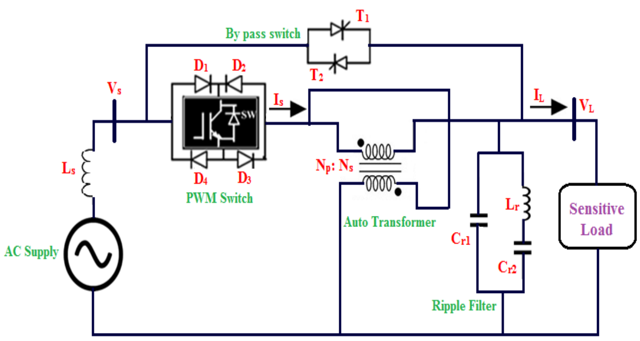

Fig. 3: Voltage sag compensation using PWM auto-transformer

The circuit consists of the following components:

IGBT: This switch is worked depending on the pulses produced by the PWM generator and controls the auto-transformer operation. Power diodes (D_1 to D_4) insert to IGBT switch controls the direction of power flow and connect in voltage controller AC system.

Autotransformer: It is controlled by a PWM operated power electronic IGBT switch and is used to boost the voltage so that the load voltage remains constant regardless of the variations in the supply voltage.

Ripple filter (RF): It is used at the output of the auto-transformer to reduce harmonics of the output voltage.

Bypass switch: It is used to bypass the auto-transformer through the normal operation. Furthermore, during the voltage sag, this switch remains off and auto-transformer works based on the IGBT switch operation to generate required voltage on the load side.

C. Control Scheme

The main function of the auto-transformer control circuit for voltage compensation is to control the pulses generated to the IGBT switch. The RMS value of the load voltage is compared with the reference value. In steady-state conditions, there is not any error and no pulses are produced to the IGBT switch and auto-transformer does not work. Otherwise, if there is a voltage sag then an error occurs, and the PWM generator produces pulses to the IGBT switch depending on the error value. The auto-transformer operates with the load voltage kept constant. When a disturbance occurs, an error voltage that is the difference between the reference RMS voltage and the load RMS voltage will be generated. The voltage error is passed across a PI controller and the control voltage value depends on the phase angle α that is proportional to the degree of disturbance. Here, the control voltage is compared with the triangular voltage for the purpose of generating the pulses fed to the IGBT switch.

5. Case studies: simulation results and analysis

This work presents the simulation results and makes a comparative study between the D-STATCOM, DVR and PWM switched auto-transformer systems. The Simulink models and system parameters are given in the Appendix.

Case study: D-STATCOM system

Voltage sag is started with D-STATCOM by connecting an extra load in the circuit model from 0.2ms to 0.4ms. The waveform of voltage sag at the PCC is illustrated in Fig. 4a. At this moment, the control configuration of the D-STATCOM is activated to produce a compensating current that is injected into the grid, and the load output voltage is regulated. The waveform of compensation current generated by D-STATCOM is depicted in Fig. 4b, indicating that the compensation current is unbalanced. The waveform of regulated output voltage is illustrated in Fig. 4c, which is kept constant at 1 pu. The total harmonic distortion (THD) of the compensated voltage is depicted in Fig. 4d. The THD is bigger due to the unbalanced nature of compensating current.

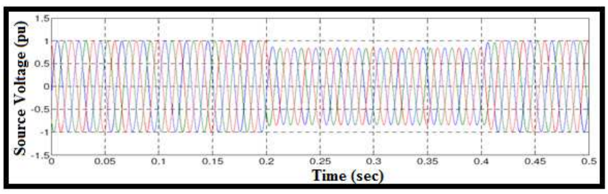

Fig. 4a: Voltage at the PCC

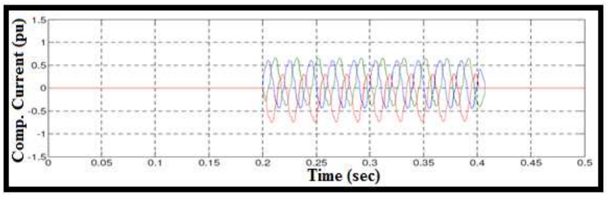

Fig. 4b: Current generated by D-STATCOM

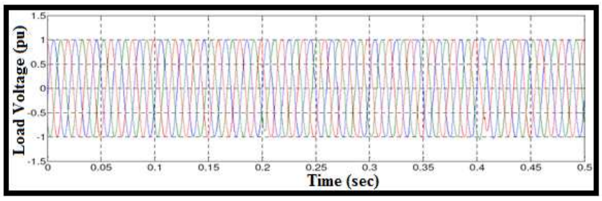

Fig. 4c: Regulated load voltage

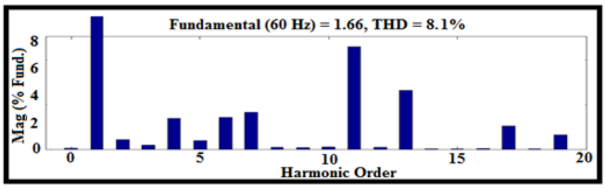

Fig. 4d: THD of compensated voltage

Case study: DVR system

Voltage sag is started in the system by inserting an extra load for certain period of the time. Here the extra load is inserted to the system from 0.2ms to 0.4ms. Therefore, during this time interval the voltage at the load bus (at the PCC) drops as illustrated in Fig. 5a. Here, the voltages are taken in pu values and the voltage sag is observed as the voltage decreases from its rated value of 1 pu. To compensate the sag in voltage, the DVR generates the compensation voltage as depicted in Fig. 5b, which is a voltage in addition to the supply voltage. The load voltage after compensation is shown in Fig. 5c, in which it is observed that DVR responds tardily to the change in voltage. Therefore, there are some imbalances at the starting and ending point of the sag due to slight error occurred in adding the compensating voltage to the system voltage. The total harmonic distortion (THD) of the load voltage is illustrated in Fig. 5d.

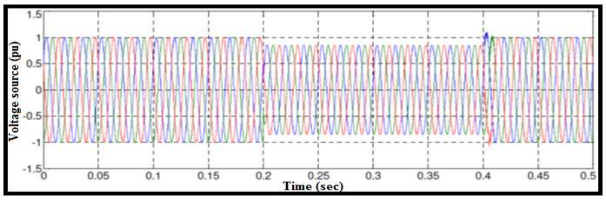

Fig. 5a: Supply voltage

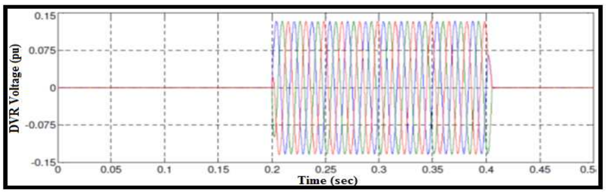

Fig. 5b: Voltage injected by the DVR

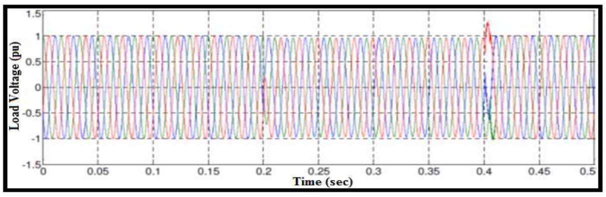

Fig. 5c: Load voltage compensated

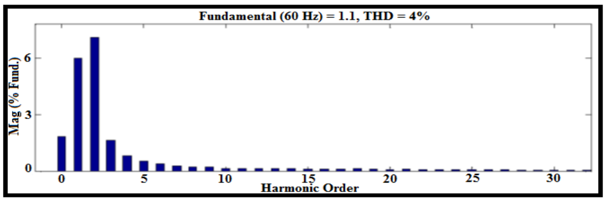

Fig. 5d: THD of the load voltage

Case study: PWM switched auto-transformer

Voltage sag is stated in the network from 0.1ms to 0.2ms and the auto-transformer operates during this interval to compensate the voltage sag. The waveform of voltage at the PCC is depicted in Fig. 6a. The waveform of voltage injected by PWM auto-transformer is shown in Fig. 6b. The waveform of regulated load voltage is illustrated in Fig. 6c, which is kept in constant value at 1pu. Finally, the total harmonic distortion (THD) of compensated voltage is depicted in Fig. 6d. From the analysis results it is obviously illustrated that, the proposed PWM switched auto-transformer is an efficient solution in compensating the voltage sag by reducing the output voltage harmonics.

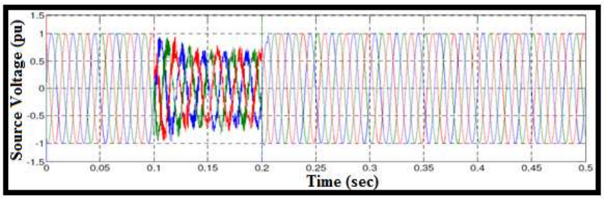

Fig. 6a: Source voltage

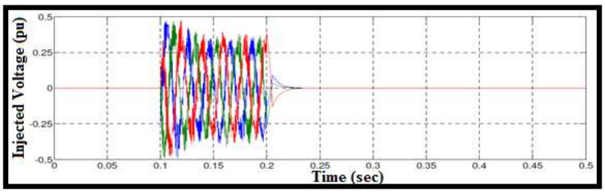

Fig. 6b: Injected voltage by PWM auto-transformer

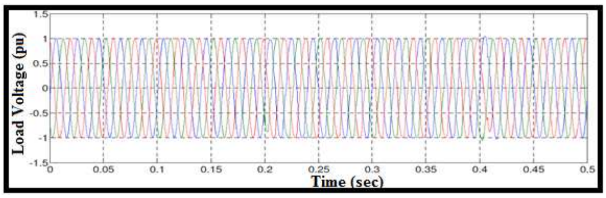

Fig. 6c: Load voltage regulated

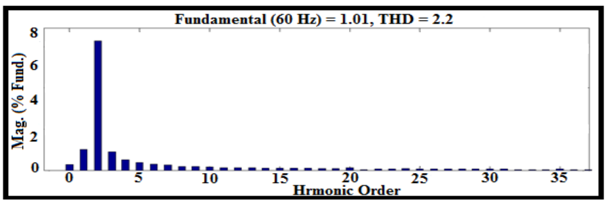

Fig. 6d: THD of compensated voltage

Case study: Comparative analysis based three systems

Based on the simulation results of D-STATCOM, DVR and PWM switched auto-transformer being carried out by using MATLAB/Simulink program, a comparative study is made among the above discussed systems regarding the compensating voltage sag and depending on the total harmonic distortion (THD) of compensated load voltage. From this research work it is observed that the proposed PWM switched auto-transformer is a more efficient solution than other devices in compensating the voltage sag. Furthermore, the advantage of PWM auto-transformer is the reduced switching losses, and less number of the switching devices needed.

6. Conclusions

Voltage sag is one of the main PQ issues that is frequently found in the electric transmission and distribution systems. In this paper, the performance analysis and simulation of D-STATCOM, DVR and proposed PWM switched auto-transformer implementation for the compensation of voltage quality issues have been presented and discussed. Here, D-STATCOM is a parallel connected device that injects current into the grid. This device is connected to the power system at the point of interest to protect the critical loads. D-STATCOM needs more numbers of power electronic switches and storage devices for working while the main task of the DVR is to inject voltage in series and in synchronism with the grid voltages that compensate voltage sags. The proposed PWM switched auto-transformer is used for compensating the voltage sag, in which the number of switches required are less and consequently the switching losses are reduced. This last sag compensation method is simple, with less size and cost and fast dynamic response because it uses only one IGBT switch per phase. The proposed technique is capable of compensating the sag by maintaining the load voltage magnitude at desired limits.

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Appendix

The following test network parameters are considered for MATLAB Simulink program.

(A) D-STATCOM system

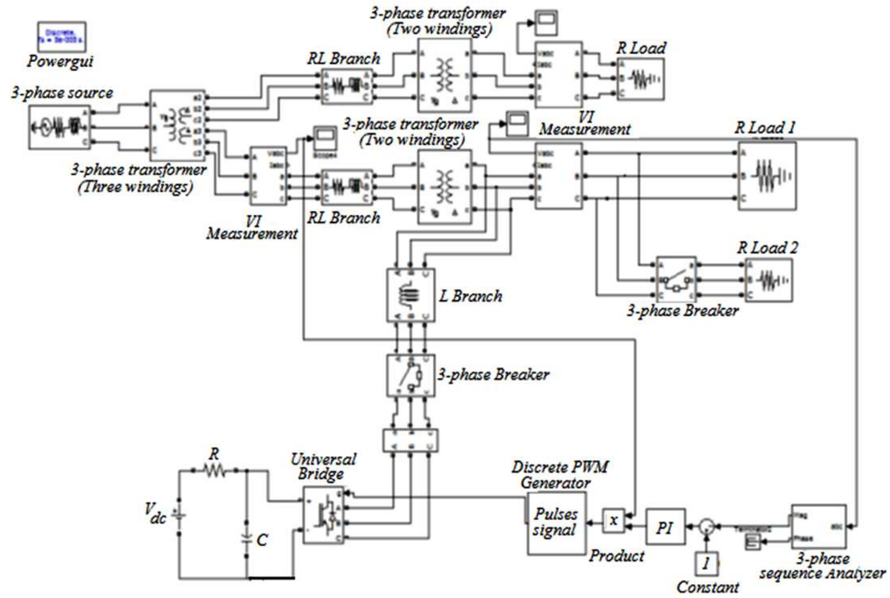
AC supply voltage 415V with 60Hz line frequency.
Magnetic coupling turns ratio 1:1
Coupling transformer Voltage = 200V.
Capacitor of D-STATCOM = 750F.
DC bus voltage of D-STATCOM = 200V.
Load active power = 20Kw.

(B) DVR system

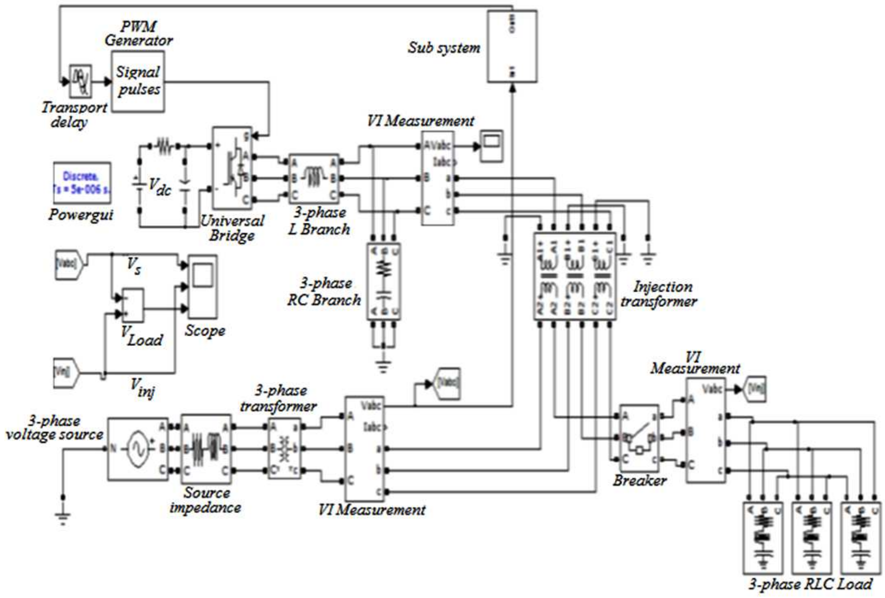
AC supply voltage 415V with 60Hz line frequency.
Series transformer turns ratio 1:1
Line impedance L_s = 0.5mH and R_s = 0.1 Ω
DC bus voltage of DVR = 100V.
Filter inductance = 1mH
Filter capacitance = 1μF
Load active power = 3KW
Load inductance = 60mH

(C) PWM Switched Auto-transformer system

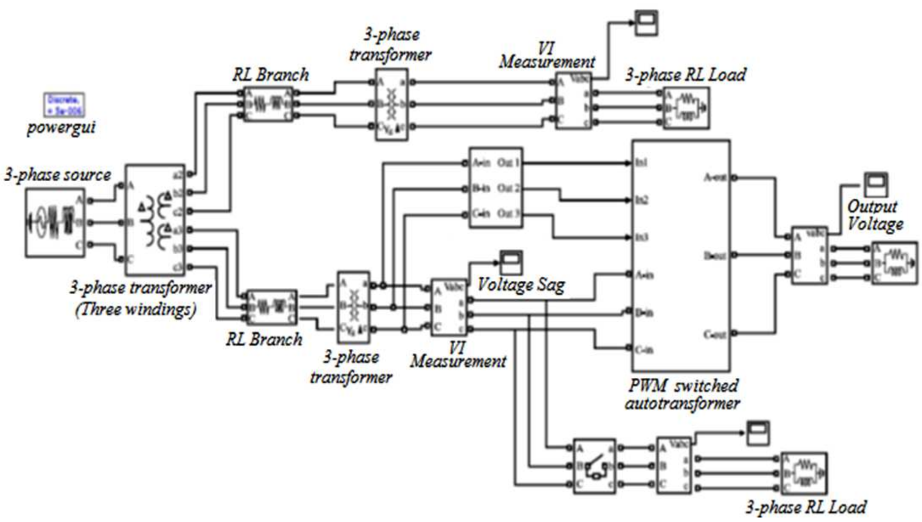
AC supply voltage 11KV, 3-phase, 100 MVA, with 60Hz frequency.
Auto-transformer primary 7 KV, 100MVA, 60Hz,
Secondary 7 KV, 100 MVA, 60Hz.
Auto-transformer ripple filter L_r=200mH, C_{r1}=C_{r2}=50μF.
Load active power = 10Kw
Load reactive power = 10Kvar.
PI controller gain K_P=10, K_i=0.5.



D-STATCOM Simulink model for sag compensation



DVR Simulink model for sag compensation



Proposed PWM switched auto-transformer Simulink model for sag compensation