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Implementation of Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (D-STATCOM) for Power Quality Improvement

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Abstract**—Power quality has become an important issue in recent times when many utilities around the world find very difficult to meet energy demands which leads to load shedding and power quality problem. Utility distribution networks, sensitivity industrial loads and critical commercial operations suffer from various types of outages and service interruptions which can cost significant financial losses. Voltage sags, swell, are the most important power quality problems which are seen in industrial and commercial installations. This research describes the improvement of power quality in a distribution system by using Dynamic Voltage Restorer (DVR) compensation and Distribution Static Compensator (D-STATCOM). From the simulation results, the voltage sags before and after compensation is improved from 0.236 per unit to 0.923 per unit respectively, while voltage swell is improved from 1.462 per unit to 1.122 per unit respectively. PSCAD/EMTDC software is using for simulation purposes.**

Keywords**— power quality, voltage sags, voltage swells, DVR, D-STATCOM**

I. INTRODUCTION

Power quality has become an important issue in recent times when many utilities around the world find very difficult to meet energy demands which leads to load shedding and power quality problem. A power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in failure or a mis-operation of end user equipments. Utility distribution networks, sensitivity industrial loads and critical commercial operations suffer from various types of outages and service interruptions which can cost significant financial losses. In order to solve power quality problems, some other remedies more than the installation of power quality monitors are needed. In connection with the rapid developments in power electronics industry, most of the semiconductors with high power capacity available for power system applications. FACTS devices use power electronics components and control method for controlling the high voltage side of the network of power systems [1]. The tendency of using electronic loads in large numbers for the last twenty years has caused many problems in power systems operation.

II. ELECTRICAL POWER SYSTEMS ARCHITECTURE

Power system has a major role to distribute electrical energy generated by generator to the consumer to fulfill the energy needs as shown in Fig.1. Broadly speaking, a power system can be grouped into three sub system such as:

A. Electricity generation system, also known as a power resource, is the process of generating electrical energy from other forms of energy.

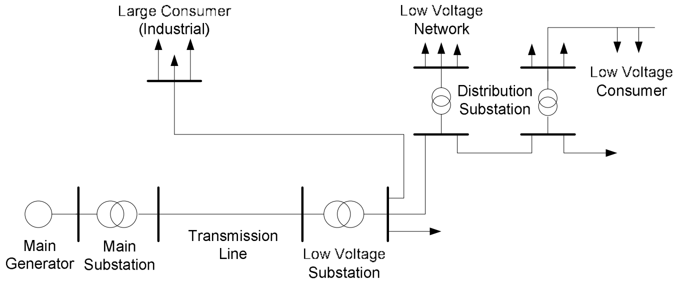

Fig.1. Distribution Network

B. Electric-power transmission system is the bulk transfer of electrical energy, from generating power plants to electrical substations located near demand centers. This is distinct from the local wiring between high-voltage substations and customers, which is typically referred to as electric power distribution. Transmission lines, when interconnected with each other, become transmission networks. Transmission system is to transmit a large-scale electric power to distribution system.

C. Electricity distribution system is the final stage in the delivery of electricity to end users. A distribution system's network carries electricity from the transmission system and delivers it to consumers. Typically, the network would

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include medium-voltage power lines, substations and pole-mounted transformers, low-voltage distribution wiring and sometimes meters.

III. VOLTAGE SAGS AND SWELLS

There are various types of disturbances influenced on maintaining the reliability of power utilities and facilities, but voltage sags of all power disturbances are considered to be a major cause of more than 80 % of PQ problems. Voltage sags are short-duration reduction in rms voltage caused by short circuits, overloads, and starting of large motors and inducing direct lightning strokes. The interest in voltage sag is mainly due to the problems they cause on several types of equipment: adjustable-speed drives, process control equipment, and computers are notorious for their sensitivity. Voltage sag is usually characterized by magnitude and duration.

Voltage sag magnitude is the rms voltage in percent (or per unit), whereas duration is the time interval of voltage sag. According to the IEEE Standard 1159 [2], [3], voltage sag is a reduction in the rms value in the range of 0.1 and 0.9 per unit for the rated voltage and its duration from 0.5 cycle to 1 minute.

Voltage swells are much less common than voltage sags and the magnitudes are not usually severe. The most common cause is a single line-to-ground fault condition. During a single line-to-ground fault, the voltage on the unfaulted phases can increase due to the zero sequence impedance. On an ungrounded system, the voltage on the unfaulted phases can be as high as 173%. On most systems, the voltage swell is less than 140%. Voltage swells can be controlled by constant voltage transformers or other types of fast-acting voltage regulators. Active power line conditioners with series elements can also control voltage swells. Many papers on DVR and D-STATCOM for power quality improvement have been successfully applied in any models of simulation [7], [8], [9].

IV. COMPUTATIONAL OF VOLTAGE SAGS AND SWELL

To calculate the amount of voltage sag / swell in radial systems, the voltage divider model can be used as shown in Fig.2.

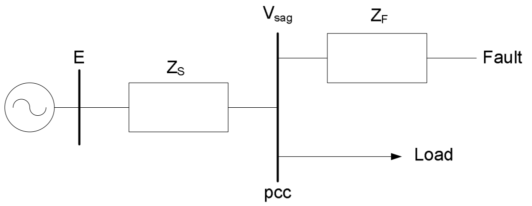

Fig.2. Voltage divider model for voltage sags/swells

In Fig. 2 we see two impedances: Z_S is the source impedance at the point-of-common coupling; and Z_F is the impedance between the point-of-common coupling and the fault. The point-of-common coupling is the point from which both the fault and the load are fed. In the voltage divider model, the load current before as well as during the fault is neglected. There is thus no voltage drop between the load and the pcc. The voltage at pcc, and thus the voltage at the equipment terminals, can be found from:

$$V_{sag/swell} = \frac{Z_F}{(Z_S+Z_F)} \cdot E \tag{1}$$

Equation (1) can be used to calculate the sag/swell magnitude as a function of the distance to the fault. Therefore, we have to write $Z_F = z_L$, with z is the impedance of the feeder per unit length and L the distance between the fault and the pcc, leading to,

$$V_{sag/swell} = \frac{Z_L}{(Z_S+Z_L)} \cdot E \tag{2}$$

V. DVR AND D-STATCOM DEVICE COMPENSATION

A. DVR Model

The DVR is a custom power device that is connected in series with the distribution system as shown in Fig.3. The main component of the DVR consists of an injection transformer, harmonic filter, VSC, an energy storage and control system. The main function of DVR is to mitigate the voltage sag, although sometimes, additional functions such as harmonics compensation and reactive power compensation are also integrated to the device.

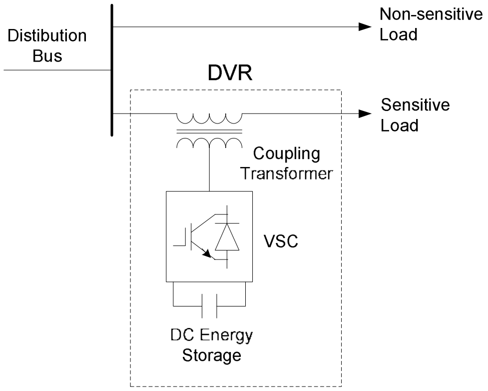

Fig.3. DVR circuit model

The circuit of Fig.3 can be represented by Thevenin equivalent circuit as shown in Fig.4a with system impedance Z_{th} depends on the fault level of the load bus. When the system voltage (V_{th}) drops, the DVR injects a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained. The series injected voltage of the DVR can be written as,

$$V_{DVR} = V_L + Z_{th}I_L - V_{th} \tag{3}$$

where V_L is the desired load voltage magnitude;
Z_{th} is the load impedance; I_L is the load current; and V_{th} is the system voltage during fault conditions.
The load current I_L is given by

$$I_L = (P_L + jQ_L)/V \quad (4)$$

Where V_L is considered as a reference equation and can be written as,

$$V_{DVR} <\propto = V_L < 0 + Z_{th} < (\beta - \theta) - V_{th} < \delta \quad (5)$$

Where α, β, δ are angels of V_{DVR}, Z_{th}, V_{th} respectively and θ is the load power angle, $\theta = \tan^{-1}(Q_L/P_L)$.

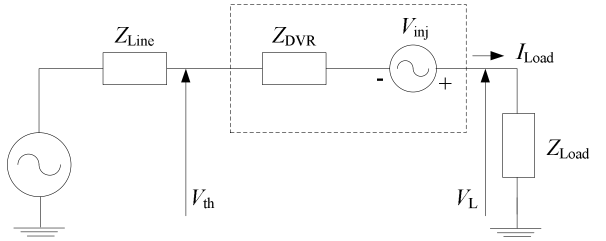

Fig.4. DVR circuit

The complex power injection of the DVR can be written as,

$$S_{DVR} = V_{DVR} \cdot I_L^* \quad (6)$$

The injection voltage is expressed as,

$$V_L(t) = V_{Sag}(t) + V_{inj}(t) \quad (7)$$

Where $V_L(t)$ is the load voltage; $V_{sag}(t)$ is the sagged voltage; and $V_{inj}(t)$ is the voltage injected by the mitigation devices as shown in Fig.4. Under nominal voltage conditions, the load power on each phase is given by,

$$S_L = V_L I_L^* = P_L - jQ_L \quad (8)$$

Where I_L is the load current, and P_L and Q_L is the active and reactive power taken by the load, respectively, during sag/swell. When the mitigation device is active and restores the voltage back to normal, the following applies to each phase,

$$S_L = P_L - jQ_L = (P_{sag} - jQ_{sag}) + (P_{inj} - jQ_{inj}) \quad (9)$$

Where the *sag* subscript refers to the sagged supply quantities and the *inj* subscript refers to quantities injected by the mitigation device.

B. D-STATCOM Model

The D-STATCOM is a three phase and shunt connected power electronics based reactive power compensation equipment, which generates and /or absorbs the reactive power whose output can be varied so as to maintain control of specific parameters of the electric power system as shown in Fig.5.

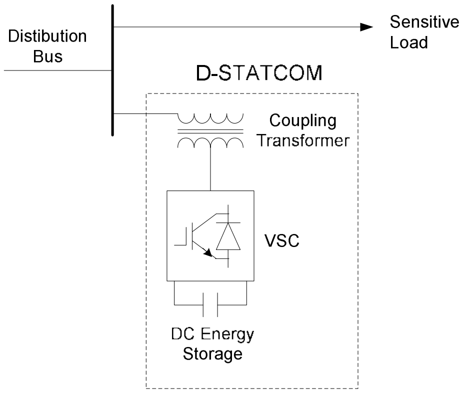

Fig.5. D-STATCOM circuit model

The D-STATCOM function is to regulate the bus voltage by absorbing or generating reactive power to the network, like a thyristor static compensator. This reactive power transfer is done through the leakage reactance of the coupling transformer by using secondary voltage in phase with the primary voltage. This voltage is provided by a voltage-source PWM inverter. The D-STATCOM acts like a capacitor generating reactive power to the bus. In steady state, due to inverter losses the bus voltage always leads the inverter voltage by a small angle to supply a small active power.

The D-STATCOM basically consists of a coupling transformer with a leakage reactance, a three phase GTO/IGBT voltage source inverter (VSI), and a dc capacitor. The ac voltage difference across the leakage reactance power exchange between the D-STATCOM and the power system, such that the ac voltages at the bus bar can be regulated to improve the voltage profile of the power system, which is primary duty of the D-STATCOM. The equivalent circuit of D-STATCOM is shown in Fig.6.

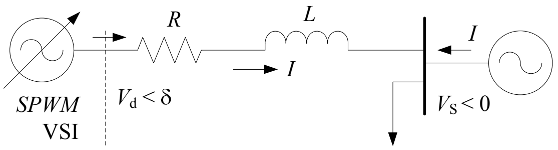

Fig.6. D-STATCOM circuit

From the figure above, the active and reactive power can be calculated by following equations:

$$P = (V_{bus} V_I / X_L) \sin \alpha \quad (10)$$
$$Q = (V_{bus}^2 / X_L) - (V_{bus} V_I / X_L) \cos \alpha \quad (11)$$

C. Voltage Source Converter (VSC)

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The VSC is used to either completely replace the voltage or to inject the *missing voltage*. The *missing voltage* is the difference between the nominal voltage and the actual. The converter is normally based on some kind of energy storage, which will supply the converter with a DC voltage. The solid-state electronics in the converter is then switched to get the desired output voltage. Normally the VSC is not only used for voltage dip mitigation, but also for other power quality issues, e.g. flicker and harmonics.

D. Pulse-width Modulation (PWM)

Pulse-width modulation (PWM) is a commonly used technique for controlling power to inertial electrical devices, made practical by modern electronic power switches. The average value of voltage and current fed to the load is controlled by turning the switch between supply and load on and off at a fast pace. The longer the switch is on compared to the off periods, the higher the power supplied to the load is. The PWM switching frequency has to be much faster than what would affect the load, which is to say the device that uses the power.

The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero. PWM also works well with digital controls, which, because of their on/off nature, can easily set the needed duty cycle.

VI. STUDY CASE AND SIMULATION RESULTS

Single line diagram of a practical radial distribution system of Feeder-1 PT. PLN (PERSERO) Kupang, East Nusa Tenggara which is used for the study is depicted in Fig.7. The system is composed of a 20 kV, 50 Hz generation system, feeding a transmission lines through a 3-winding transformer connected in Y/Δ/Y, 150/20/20 kV. Such transmission lines feeding a distribution networks through transformers connected in Y/Δ, 20/0.380 kV. There are twenty seven substations and 40 buses loads of totalling 2311.675 MW and 959.785 MVAR. PSCAD/EMTDC [4] is an industry standard simulation tool for studying the transient behaviour of electrical networks. With the help of PSCAD/EMTDC software as a tools for simulating the system, it was performed the fault condition, voltage sag and swell profile before and after installing the DVR and D-STATCOM circuits.

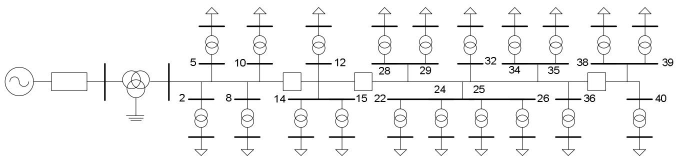

Fig.7. Single line diagram of Feeder-1 PT. PLN (PERSERO) Kupang

A. Voltage Sags

Case 1: Simulation results of rms voltage at base case

The first simulation is to perform the system profiles in base case condition at no fault applied and no compensation devices. From the simulation result, the rms voltage and power flow profile of the system are shown in Fig.8 and Fig.9 respectively. It can be seen from Fig.8, the rms voltage is 1.0 per unit. This voltage profiles will interrupt in certain time based on the fault applied in the system.

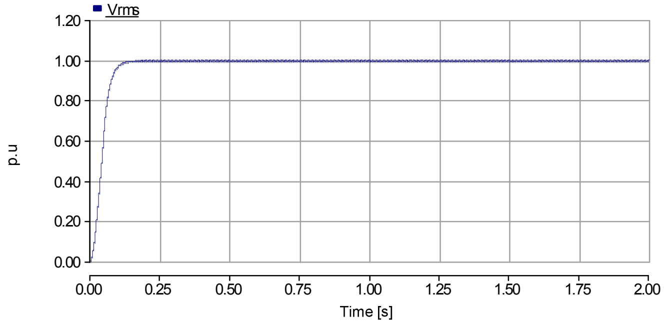

Fig.8. RMS voltage profiles of the system at base case

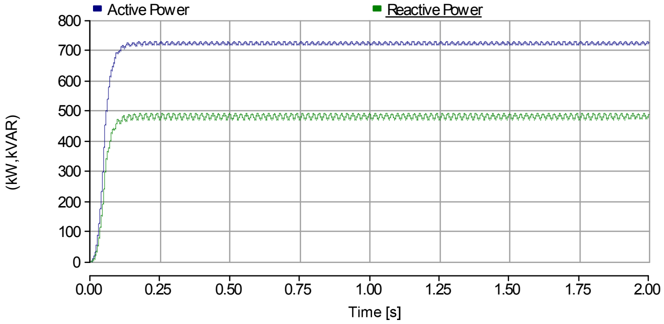

Fig.9. Active and reactive power flow at Node 5 at base case

It shows from the Fig.9 that the active and reactive power flow through Node 5 are 721.006 kW and 488.648 kVAR respectively, while the load voltage and phase-angle are shown in Fig.10.

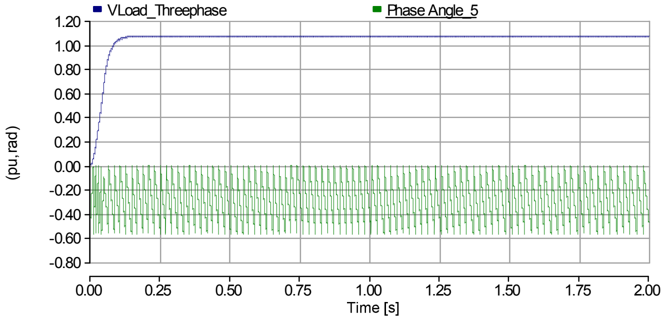

Fig.10. Load voltage and phase-angle profile at Node 5

Case 2: Simulation results of voltage sags during three- phase to ground fault with no DVR and D-STATCOM device

The second simulation is performed the system contains no DVR and three-phase to ground fault is applied at 20 kV side of the distribution transformer via a fault resistance of 0.8 Ω, during the period of 300ms. When a three-phase to ground fault is applied to the system at the time of 1.2 seconds for duration of 300ms, the rms voltage is felt down to approximately 0.23 per unit as shown in Fig.11. The load voltage and the phase-angle were captured at Node 5 as shown in Fig.12. The active and reactive power flow profile at Node

5 during the three-phase to ground fault is also felt down to small amount as shown in Fig.13.

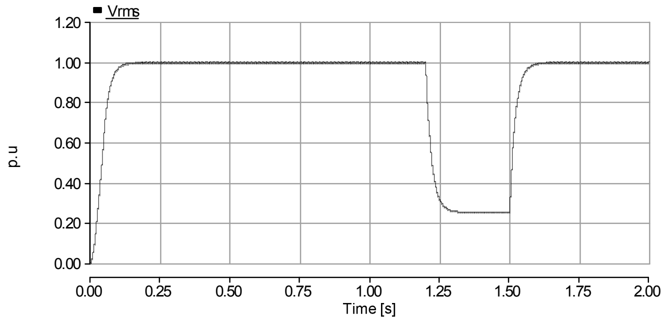

Fig.11. Voltage sag profiles when three-phase fault applied and no compensation devices

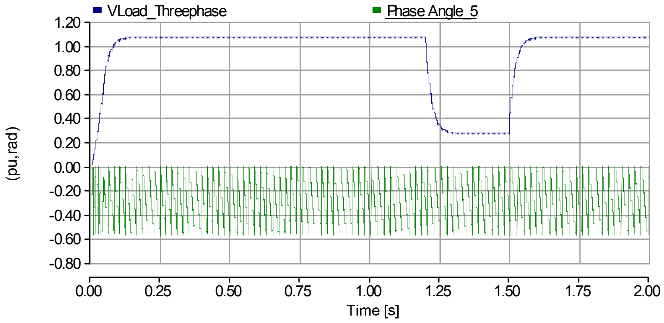

Fig.12. Load voltage and phase-angle profile at Node 5 when three-phase fault applied and no compensation devices

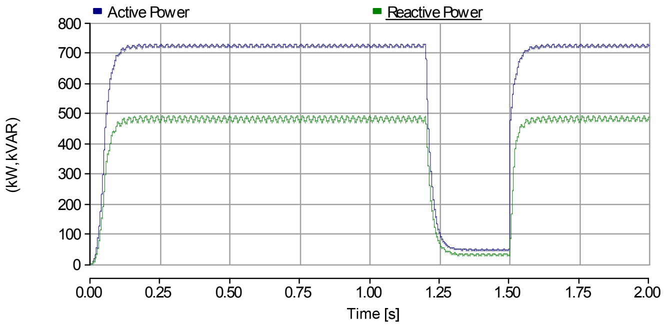

Fig.13. Active and reactive power profile during three-phase to ground fault at Node 5

Case 3: Simulation results of voltage sags during three- phase to ground fault with DVR devices

Similarly, a new set of simulations was carried out but now with the DVR connected to the system, the rms voltage, load voltage, phase-angle and the power profile at Node 5 are shown in Fig.14, Fig.15, and Fig.16 respectively.

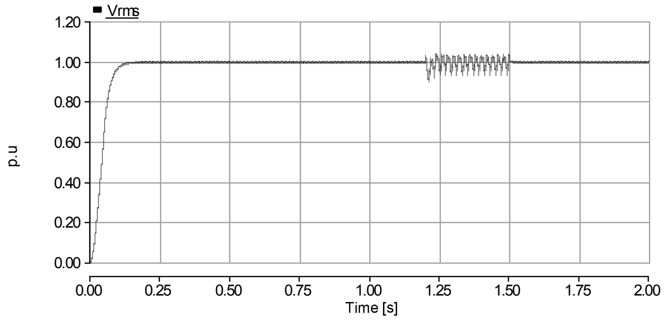

Fig.14. Voltage sag profiles with DVR compensation.

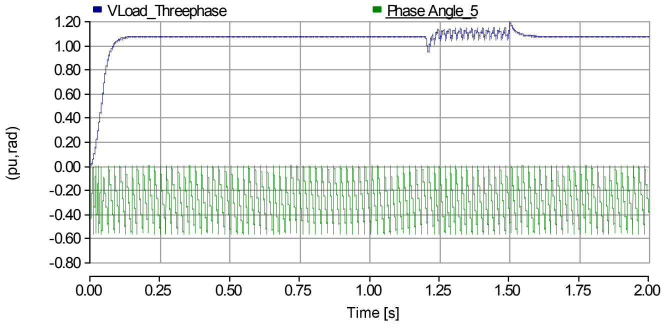

Fig.15. Load voltage and phase-angle profile with DVR compensation

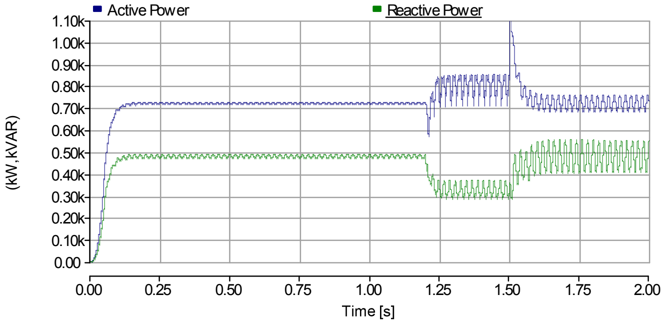

Fig.16. Active and reactive power profile with DVR compensation

The simulation carried out showed that the DVR provides excellent voltage regulation capabilities.

Case 4: Simulation results of voltage sags during three- phase to ground fault with D-STATCOM devices

In this case, a set of simulations was carried out but now with the D-STATCOM connected to the system. The voltage sag and phase-angle and the active and reactive power profile at Node 5 of the system are shown in Fig.17 and Fig.18 respectively. The load voltage magnitude is 1.0487 per unit and the active and reactive power flow is 692.162 kW and 469.817 kVAR respectively. It can be seen that the voltage across load at Node 5 decreases and resumes to the rated value due to the injection of voltage by the D-STATCOM. Thus the D-STATCOM is able to mitigate the voltage sag produced by the additional load.

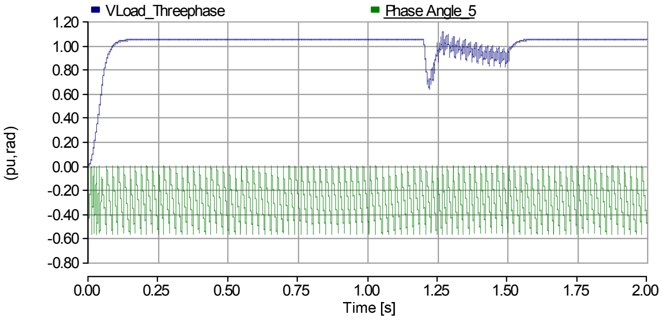

Fig.17. Load voltage and phase-angle profile at node 5 of the system

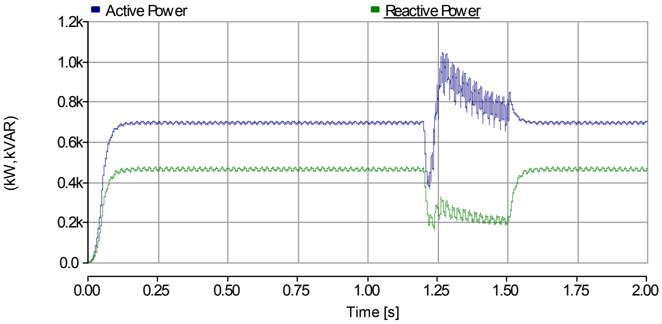

Fig.18. Active and reactive power profile at Node 5

Power quality is improved since the voltage almost reaches normal value.

B. Voltage Swells

Case 5: Simulation results of voltage swells with no D-STATCOM devices

To investigate the voltage swells profiles in the system, a bank capacitor of certain capacity is installed in the primary side of the 150kV transformer without D-STATCOM. The simulation is running to see the voltage swell and the power profile at Node 5 of the system as illustrated in Fig.20. It can be observed from the figure that the voltage increased by 50% from the reference voltage and the load voltage at Node 5 is also increased as shown in Fig.20. The active and reactive power flows are increased at Node 5 since the capacitor bank is support such amount of reactive power to the system, as shown in Fig.21. It is also recorded the active power and reactive power flow at Node 5 are 694.783 kW and 475.185 kVAR respectively.

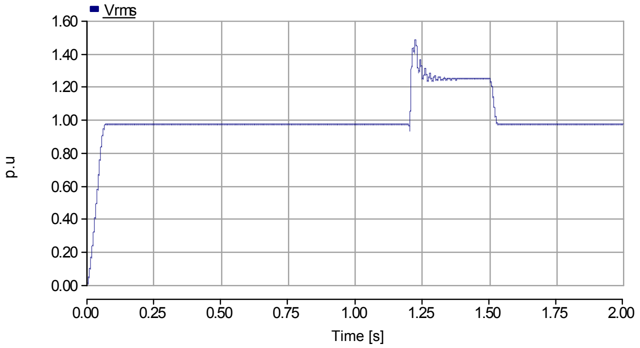

Fig.19. Voltage swells profiles of the system

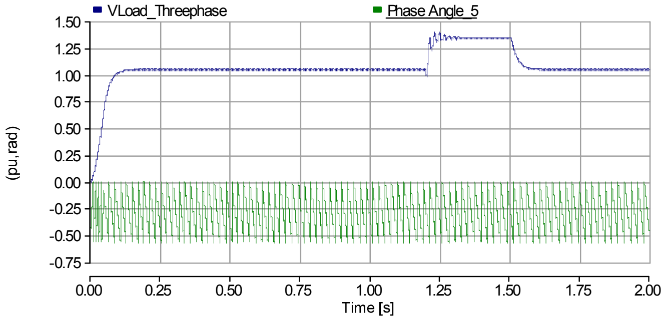

Fig.20. Load voltage and phase-angle profile at Node 5

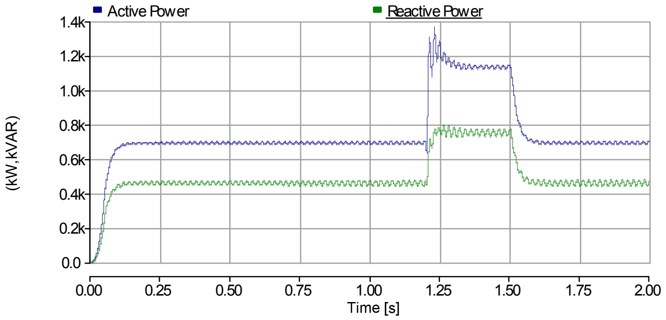

Fig.21. Active and reactive power profile at Node 5

Case 6: Simulation results of voltage swells with D-STATCOM devices

To reduce of the voltage swells during the capacitor bank operation, a D-STATOM as compensation devices is applied to the system.

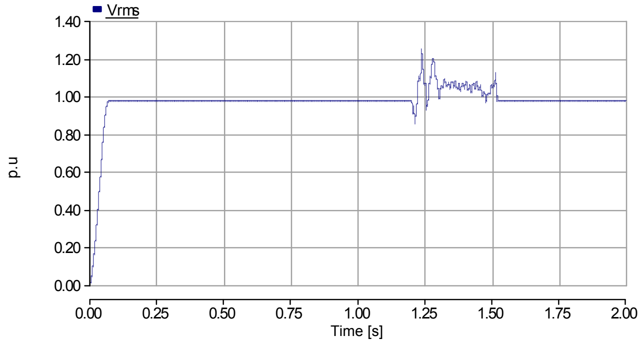

Fig.22. Voltage swells profiles after installing D-STATCOM

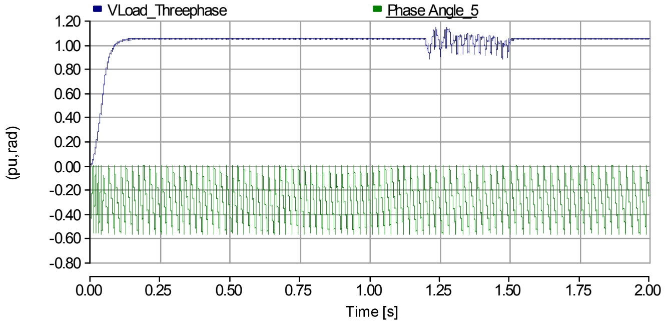

Fig.23. Load voltage and phase-angle profile at Node 5

The parameters such as voltage swell, load voltage, phase-angle and the power profile are shown in Fig. 22, Fig.23, and Fig.24, respectively. The active and reactive power flows are reduced since the capacitor bank is absorbed such amount of active and reactive power from the system. It is also recorded the active power was reduced to and reactive power at Node 5 are reduce to 692.814 kW and reactive power was increased to 478.146 kVAR.

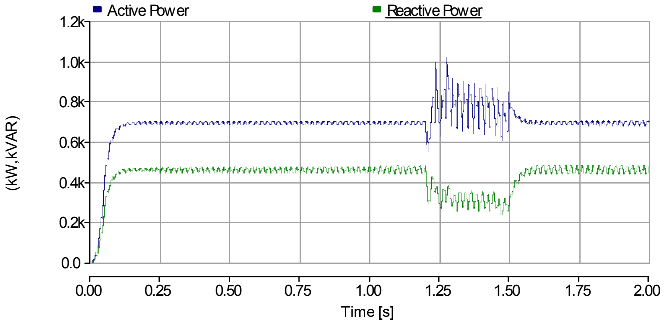

Fig.25. Active and reactive power profile at Node 5

VII. CONCLUSION

A detailed model of DVR and D-STATCOM has been developed for use in PSCAD/EMTP. Models of both power circuit and control system have been implemented in a practical distribution system of 20kV PT. PLN KUPANG (PERSERO). The simulations carried out demonstrated that DVR and D-STATCOM provide excellent improvement of power quality such as improving the voltage sags and swells.

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