Jurnal
Teknologi

Full Paper

Voltage Level Control in Weak Distribution Networks with DG by Using Hybrid Reactive Power Compensations

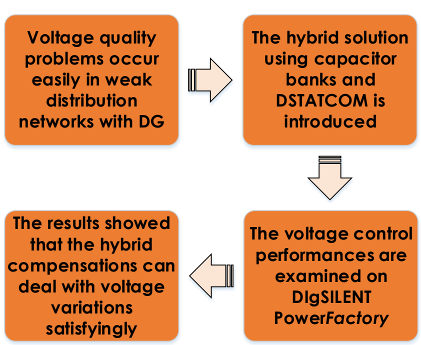
Piyadanai Pachanapan*

Faculty of Engineering, Naresuan University, Thailand

Article history
Received
23 July 2015
Received in revised form
28 November 2015
Accepted
21 January 2016

*Corresponding author
piyadanip@nu.ac.th

Graphical abstract



Abstract

The hybrid reactive power compensations, using capacitor banks and distribution static compensator (DSTATCOM) in the coordinated manner, are introduced to enhance voltage level control performances in weak distribution networks with the increasing of distributed generation (DG), such as in the rural areas. While the conventional compensation using capacitor banks gives the poor dynamic voltage control, these hybrid compensations are the cost effective solution which can deal with both under-and over-voltage changes, either short- or long duration voltage variations. The dynamic voltage control performances are demonstrated under various operating scenarios using the test system implemented in DIgSILENT*PowerFactory*. The simulation results showed that this approach can improve voltage controllability in weak distribution networks with DG effectively.

Keywords: Hybrid reactive power compensations; DSTATCOM; capacitor banks

1.0 INTRODUCTION

Many rural areas, especially in the hills, are connected to the main grid via the long distribution line, which causes the network strength in those areas is relatively weak. As the power quality is concerned, the load and distributed generation (DG) connected to weak networks are easy to face the under-and over-voltage problems. The self-excited induction generators, such as small wind and hydro power plants, are extensively used as DG in such remote locations. The modern induction generator is a brushless construction with squirrel-cage rotor which can run for years without maintenance, rugged and less maintenance cost and better transient characteristics [1]. However, this type of DG cannot support the reactive power for the voltage control by itself, unlike the conventional synchronous generator or converter connected DG.

The conventional solution to improve voltage quality is using the shunt capacitor banks, typically installing parallels with the DG at the point of common coupling (PCC). However, the capacitor banks can only inject the reactive power into the network allowing it can merely be used for voltage drop problems. Furthermore, the control response of capacitor banks is rather slow, letting it is difficult to deal with the relatively short duration variations such as instantaneous and momentary voltage sags. These limitations cause the capacitor banks hard to comply with the requirements in many established international standards such as IEEE 1159-2009, EN50160 and IEC 61000.

Modern power conditioning devices based on voltage source converter (VSC), such as a distribution static compensator (DSTATCOM), can offer fast controllability and adapt to changes in network conditions. The DSTATCOM has the potential to support either short- or long-duration variations and it can provide both inductive and capacitive reactive power into the network, making it is able to improve either under- or over-voltage problems. Moreover, the DSTATCOM is already used to mitigate the power quality problems in many applications such as voltage sag, flicker, voltage unbalance and harmonics, as the comprehensive review in [2]. Although, DSTATCOM gives a good performance in dynamic voltage control, it is very expensive.

As the cost of capacitor banks is much cheaper comparing to the DSTATCOM (about 20% of DSTATCOM[3]), using the hybrid reactive power compensations from capacitor banks and DSTATCOM, proposed in [4],[5],are a promising approach to improve the voltage quality with the cost effective. The amount of reactive power will be shared between shunt capacitors and DSTATCOM which can give benefits in the reducing of initial investment and life cycle cost. In addition, the sizes of shunt capacitors and DSTATCOM should be chosen carefully to ensure that they can success either power factor or voltage target with the satisfy performance. Despite the voltage control performance by the hybrid compensations is not good as the using of pure DSTATCOM, it can cover the most voltage qualtiy problems sufficiently with the lower cost.

2.0 REACTIVE COMPENSATION DEVICES

In this section, the general detail of capacitor banks and DSTATCOM is described.

2.1 Capacitor Banks

The conventional capacitor banks control is a fixed switching program which the shunt capacitor relays are switched-in or switched-off, in sequence, until voltage level or power factor reaches the desired value or remains within the statutory range. The examples of fixed switching programs for equal- or unequal-size capacitors are demonstrated in [6]. Alternatively, the modern capacitor banks control is picking out the correct capacitor size by referring to the actual demand of reactive power directly, which can provide the fast control response. Additionally, the switching controllers enable to calculate the exact value of reactive power and thento select a group of shunt capacitors suitably.

2.2 DSTATCOM

The DSTATCOM, is a power converter based reactive power compensator, which can compensate reactive power in a minimum of two cycles [7]. It comprises a voltage source converter (VSC), a DC capacitor and a coupling transformer, as illustrated in Figure 1. The reactive power supplied by the DSTATCOM is controlled by the magnitude difference between the AC system voltage, V_S, and the VSC voltage, V_t,while the active power flow is normally set as zero [8].

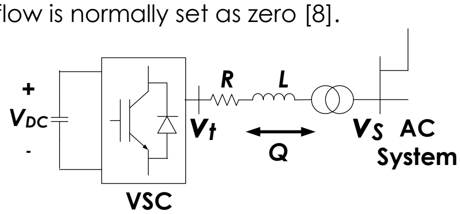


Figure 1 Simplified model of DSTATCOM-AC network

The control scheme of DSTATCOM is developed based on the *dq* synchronous rotating reference frame which decouples the control for the real and imaginary current components. This control method consists of two main classes of two dimensional frames, the *αβ*-frame and the *dq*-frame called the stationary frame and the rotating frame respectively.

Adapting from [9], the *αβ*-frame is the transformation from *abc* frame into the Cartesian coordinate system where real and imaginary parts of current from the transformation are function of time. If $i(t)$ is the current-controlled signal, that is, time-varying function, the transformation from three phase *abc*-frame into *αβ*-frame using Clark's transformer can be written as:

$$\begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \quad (1)$$

The Park's transformation from *αβ*-frame to *dq*-frame can be represented as:

$$\begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} = \begin{bmatrix} \cos\varepsilon(t) & \sin\varepsilon(t) \\ -\sin\varepsilon(t) & \cos\varepsilon(t) \end{bmatrix}\begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \end{bmatrix} \quad (2)$$

In case of a constant-frequency system, $\varepsilon = \varepsilon_0 + \omega_0 t$, where$\omega_0$is the AC system operating frequency and $\varepsilon_0$is an initial phase angle between the real axis of the *αβ*– and *dq*- frames (constant value). Theεcan be obtained by using a phase-lock loop (PLL), in case of a grid–connected DSTATCOM system. On the other hand, the *dq*-frame can be converted back to the *abc*-frame using the inverse transformation of (1) and (2) as:

$$\begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} \cos\varepsilon(t) & -\sin\varepsilon(t) \\ \sin\varepsilon(t) & \cos\varepsilon(t) \end{bmatrix}\begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} \quad (3)$$

The controller diagram of the DSTATCOM based on the *dq*-synchronous reference frame is demonstrated in Figure 2. The close-loop control consists of two cascaded control loops to control *P* and Q exchanged by the DSTATCOM with the AC network. In this scheme, the outer controller is slower than the inner controller. The two current components, i_d and i_q, are controlled independently. The reference value for the *d*-axis current is provided by the *P* controller, whilst the reference value for the *q*-axis current is provided by the *Q* controller. In both control loops the error signals are compensated using PI controllers.

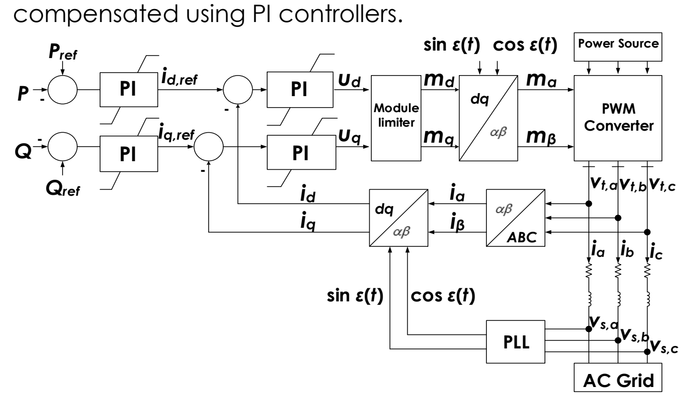


Figure 2 VSC controller in DSTATCOM

The u_d and u_q from the inner-current controllers are the input signals to the pulse width modulation (PWM) generators, which are limited to ensure that PWM operates in its linear range. Those input voltages will be referred to the modulation index signals, m_d and m_q, in the *dq*-frame, which are converted to the *αβ*-frame and then to the real and imaginary voltages are calculated using (4). Thus, the *dq* voltages of the DSTATCOOM can be transformed into three-phase voltages by transforming from *αβ*-frame to *abc*-frame.

$$\begin{aligned} v_{t,\alpha}(t) &= k_o m_\alpha(t) V_{dc}(t) \\ v_{t,\beta}(t) &= k_o m_\beta(t) V_{dc}(t) \end{aligned} \quad (4)$$

where $V_{t,\alpha}$ and $V_{t,\beta}$ are the real and imaginary part of the rms terminal voltage of DSTATCOM, respectively. Similarly, m_α and m_β are real and imaginary part of the modulation index, respectively. k_o is a constant factor that depends on the modulation method. k_o is $\sqrt{3}/(2\sqrt{2})$ in case of the Sinusoidal PWM [10].

3.0 VOLTAGE CONTROL STRUCTURE

The coordinated voltage control manner between capacitor banks and DSTATCOM is implemented to enhance the voltage control performance at the PCC. Additionally, the control operations of capacitor banks voltage controller and DSTATCOM voltage controller are also explained.

3.1 Coordinated Voltage Controllers

The DSTATCOM is set as the primary controller which uses the VSC to adjust the reactive power output with the fast response. The DSTATCOM voltage controller starts to provide the reactive power compensations when either the level of voltage change (ΔV) is higher than the voltage dead band (V_{DB}) or voltage level is out of the lower or upper limit, defined as $V_{DSTATCOM,lower}$ and $V_{DSTATCOM,upper}$, respectively.

The capacitor voltage controller aims to deal with the slow voltage variations in case of the reactive power supported by the DSTATCOM is insufficient. The reactive power injected from shunt capacitors is controlled by switching each shunt capacitor relay, one-by-one, until the voltage level at the PCC stays within the acceptable range defined as $V_{CAP,lower}$ and $V_{CAP,upper}$ for lower and upper voltage control limits, respectively. A time delay is added to this controller to ensure that the DSTATCOM already supports voltage control and to prevent the capacitor banks from supporting short-term voltage variations.

The coordination between capacitor banks and DSTATCOM is implemented by defining the gap between voltage control limits, as shown in (5) and (6). The gap between the voltage limits of capacitor bank and DSTATCOM should be wide enough to allow the reactive power compensation from the DSTATCOM to reach its capacity or using as much as possible, before the capacitor banks start the voltage control process.

$$V_{DSTATCOM,lower} > V_{CAP,lower} > V_{STAT,lower} \quad (5)$$

$$V_{DSTATCOM,upper} < V_{CAP,upper} < V_{STAT,upper} \quad (6)$$

where $V_{STAT,lower}$ and $V_{STAT,upper}$ are lower and upper statutory voltage limits, respectively.

3.2 Capacitor Banks Voltage Controller

The fixed switched program method is chosen to control the switching of shunt capacitor relays, because of it is simple and effective enough for slow voltage control. The shunt capacitor relays are switched in sequence until the voltage level at the PCC stays within the acceptable range. Although the picked up method can provide the faster reactive power support, the relativity of the changes of voltage and reactive power, $\Delta V/\Delta Q$, needs to be known for calculating the exact value of reactive power required from the capacitor banks.

The shunt capacitor relays start to switch-in when the voltage level at the PCC is below the lower voltage control limit. In contrast, the shunt capacitor relays start to switch-off, to disconnect the shunt capacitors from the network, when the voltage level at PCC is over the upper voltage control limit. The sequence of relays switching can be determined according to a linear or a circular switching sequence[11].

3.3 DSTATCOM Voltage Controller

Under normal conditions, the DSTATCOM will maintain the reactive power at constant value such as at the unity power factor while the active power is zero. The DSTATCOM provides the active voltage control by adjusting its reactive power output. The voltage controller is added as an optional outer control loop to the *Q* controller (see Figure 2.) which can be connected or disconnected from the main controller depending on the voltage level. The reference value of *P* controller is set to zero to make the DSTATCOM supports only the reactive power.

The DSTATCOM can enter the voltage control mode automatically when the level of voltage change is greater than the dead-band value or when it is out of the voltage control limit. The PI controller with limiter function is used as the compensator. The limiter function is used to limit the amount of reactive power support from DSTATCOM to avoid overloading the converter. The structure of the DSTATCOM voltage controller mode is illustrated in Figure 3.

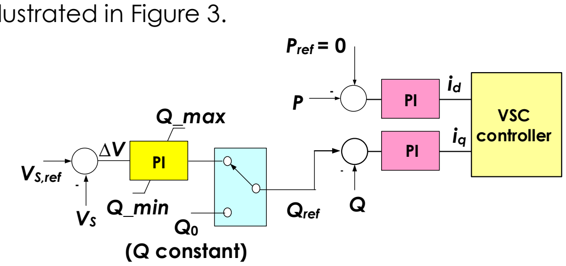


Figure 3 DSTATCOM voltage controller

4.0 TEST SYSTEM AND CASE STUDIES

The 22 kV, 50 Hz test system is shown in Figure 4. The capacity of DG is 2 MW, assuming it is the induction generator type. The DG is integrated into the main grid via the relatively long distribution line, which the line impedance is 17.15 + *j*17.92 Ω. The initial condition is set as the DG supplied 1.5 MW at unity power factor, the load demand is 1.5 MW at 0.85 power factor lagging, and capacitor banks and DSTATCOM are not included. The result from load flow calculation shows that the voltage at PCC is about 0.98 p.u. while the voltage at the main grid is 1.01 p.u..

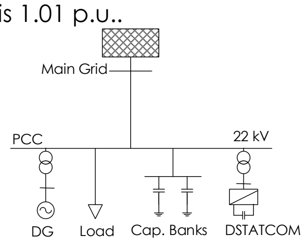


Figure 4 Test system

The value of voltage change at the PCC can be estimated by using *V/Q* curve, plotted on DIgSILENT*PowerFactory* software. Based on the initial condition, the *V/Q* curve is shown in Figure 5. It is found that the voltage level at the PCC is changed approximately 0.038 p.u. when reactive power is adjusted 1 MVar. Hence, the Q = +1.6 MVar is required if assuming the voltage level at the PCC can be raised up to nearly+0.06p.u.. Due to the price of capacitor bank is a lot cheaper comparing to the DSTATCOM, the amount of reactive power support is given weight to the capacitor banks. In addition, the size of shunt capacitor should not be larger than 70% of the rated total compensation capacity, as recommended in [12]. Assuming the investment cost in capacitor banks is 20% of DSTATCOM, installing DSTATCOM and capacitor banks at the sizes of 0.6 MVar and 1.0 MVar, respectively, can save the cost about 50% when comparing to the use of only DSTATCOM at the size of 1.6 MVar.

The number and size of shunt capacitors should be suitable to ensure that the shunt capacitors can meet both power factor and voltage control targets, with the reasonable cost. In this test, a set of 4×0.25 MVar shunt capacitors is employed. The DSTATCOM can support ±0.6 MVar. They are able to give the capability of reactive power compensation in range of -0.6 MVar (inductive) to +1.6 MVar (capacitive). This means that hybrid reactive power compensations are able to approximately adjust the voltage level at the PCC to decrease by 0.02 p.u or to increase by 0.06 p.u..

The voltage controller on the *q*-axis of DSTATCOM, in Figure 3, will start when the ΔV at the PCC is higher than the V_{DB}=0.015 p.u., or the voltage level is outside the allowed limits, between $V_{DSTATCOM,lower}$= 0.96 p.u.and $V_{DSTATCOM,upper}$=1.04 p.u.. Moreover, the PI controllers' gains in DSTATCOM voltage controller (see in the Appendix) obtained by fine tuning using Zeigler and Nicole method [13]. Alternatively, the metaheuristics optimization algorithms such as BSOA [14] can be used for finding the optimal tuning of DSTATCOM controllers.

The capacitor banks voltage controller scans the voltage level at the PCC every 2 s while the DSTATCOM voltage controller updates the PCC's voltage in every 0.5 s. The linear switching sequence is employed which the capacitor banks are switched in in ascending order and switched off in descending order of indices. Furthermore, a time delay of 2 s is added into the controller to prevent it from providing short-term voltage support and to ensure that the DSTATCOM voltage controller will operate first. Hence, a time consuming for switching each shunt capacitor is assumed to be 4 s.

To coordinate the voltage controller between DSTATCOM and capacitor banks, using (5) and (6), $V_{CAP,lower}$is set as 0.955 p.u. and $V_{CAP,upper}$is set as 1.045 p.u.. The statutory voltage limits are 1±0.05 p.u.

The dynamic performances of the coordinated voltage controller strategy between DSTATCOM and capacitor banks is investigated by transient simulations on DIgSILENT*PowerFactory*software. The short-term voltage variation is examined in the event of a small voltage sag by applying a three-phase short-circuit through a high impedance in the main grid, between*t*=1 s and *t* =2.5 s. Furthermore, the slow voltage variations are implemented by applying a gradual increasing and decreasing local load demand, start at *t* = 10 s, as shown in Figure 6. Assuming all shunt capacitors are disconnected at the initial condition.

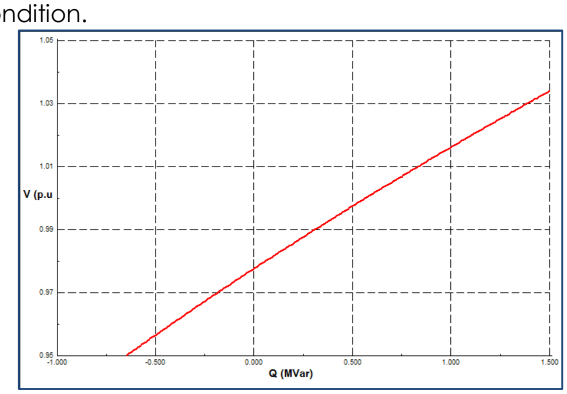


Figure 5 *V/Q* curve at the PCC

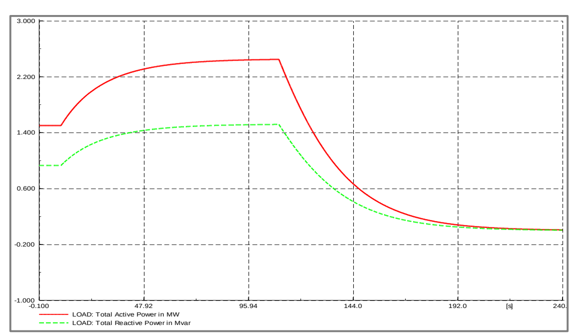


Figure 6 Change of total load demand

The study is the comparison between 3 cases, including;

1) No reactive power compensation (based case).
2) Only capacitor banks support the voltage control at 1.6 MVAR (4×0.4 MVar)
3) DSTATCOM at 0.6 MVar and capacitor banks at 4×0.25 MVar provide the voltage control.

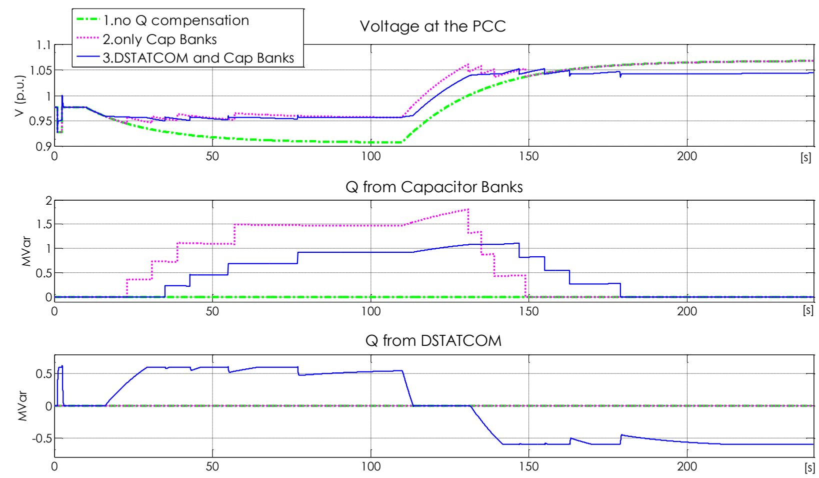
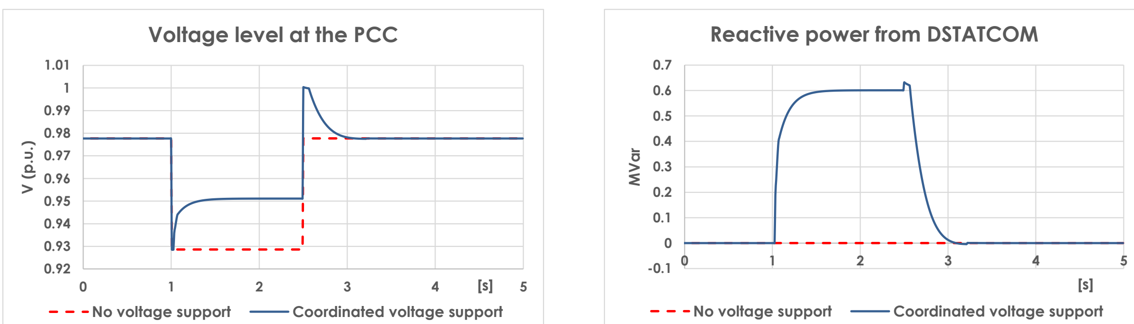


Figure 7 Voltage level at the PCC and reactive powers of DSTATCOM and capacitor banks



(a) (b)

Figure 8 Voltage compensation during voltage sag occurs

5.0 SIMULATIONS AND RESULTS

The simulation results are the comparison between those 3 cases. The changes of rms voltage at the PCC and The reactive power, Q, of capacitor banks and DSTATCOM are shown in Figure 7. The zoom-in windows of voltage at PCC and Q from DSTATCOM, during the voltage sag occurs, are shown in Figure 8.

5.1 Short-term Voltage Control

The transient results in Figure 8, show that the fast voltage control from DSTATCOM can deal with the voltage sag effectively. It is found that the change of reactive power generation, from 0 MVar to +0.6 MVar, can enhance the voltage controllability at PCC, about +0.022 p.u. which can bring the voltage level back in the statutory limit (>0.95 p.u) within 1 s. It is found that voltage spikes are introduced after the disturbance is cleared because some reactive power is still being supplied by the DSTATCOM. However, the voltage is recovered to its nominal value within approximately 1 s. Moreover, there is no voltage support from the shunt capacitors due to the time delay of 2 s is added, to prevent them providing the compensation during the fast voltage variations.

5.2 Long-term Voltage Control

From Figure 7, the voltage control at the PCC is not sufficient in cast of using only a 4×0.4 MVar capacitor banks. It can be seen that the capacitor banks cannot deal with short term voltage sag. Furthermore, shunt capacitors are unable to prevent the voltage level to above the statutory limit due to the lacking of absorbing reactive power capability.

In case of hybrid reactive power compensations, during the heavy loading condition (voltage level is decreasing), the reactive support from DSTATCOM starts to compensate the voltage level at the PCC when it is lower than $V_{DSTATCOM,lower}$, at $t \approx 16$ s. The reactive power from DSTATCOM has increased gradually to prevent the voltage drop. However, at $t\approx$ 31 s, the reactive power compensation from DSTATCOM reaches the limit while voltage level starts to below the $V_{CAP,lower}$(< 0.955 p.u.). Then, the capacitor banks voltage controller will operate as the secondary support by switching each shunt capacitor into the network until the voltage level at the PCC stays within the voltage control limits.

The shunt capacitor relays are switched at $t \approx 35$ s, $t \approx 43$ s, $t \approx 55$ s and $t \approx 77$ s, respectively. It uses 4×0.25 MVar shunt capacitors to bring the voltage at the PCC back within statutory limits. In addition, the DSTATCOM will reduce the Q support if the shunt capacitors can bring the voltage level to above the $V_{DSTATCOM,lower}$. A set of shunt capacitors remains connected despite the network is back to normal condition which can results the increasing of voltage level during normal and light load conditions.

To deal with the voltage rise problem, the DSTATCOM starts supporting reactive power after the voltage level at the PCC is higher than $V_{DSTATCOM,upper}$ since $t \approx 131$ s. At $t \approx 142$ s, the reactive power compensation from DSTATCOM is insufficient, which the voltage level starts to above the $V_{CAP,upper}$(>1.045 p.u.). Hence, the shunt capacitors are disconnected from the system, at$t\approx$ 146 s, $t \approx 154$ s, $t \approx 162$ s and $t \approx 178$ s, respectively, to reduce the voltage level at the PCC. It is found that hybrid reactive power compensations by using capacitor banks and DSTATCOM with the coordinated manner can control the voltage level at the PCC within the statutory range, with the satisfy control response.

Table 1 Parameters of DSTATCOM

Device	Parameters
VSC	0.6 MVA, V_{dc}= 1 kV, v_t = 0.4 kV
DC capacitor	C = 0.019 F (5% peak to peak voltage ripple)
reactor	R = 0.0005 Ω, L = 0.017mH
Transformer	1.25 MVA, 0.4/22 kV, $V_{S/C}$ = 6 %X/R = 7.14

Table 2 PI controllers' gains of DSTATCOM

Controllers	Gain parameters	
i_d controller	K_{id} = 0.2	T_{id} = 0.08
i_q controller	K_{iq} = 0.2	T_{iq} = 0.08
P controller	K_P = 0.7	T_P = 0.08
Q controller	K_Q = 0.6	T_Q = 0.1
V controller	K_V = 20	T_V = 0.1 (Voltage control)

6.0 CONCLUSION

The coordinated voltage controllers between DSTATCOM and capacitor banks can enhance voltage quality to the weak distribution networks with DG connection, both short- and long-term voltage variations. The results from simulations showed that the DSTATCOM can give the fast voltage control response making it can deal with short term voltage. The capacitor banks can improve voltage capability by supporting the slow voltage control when the reactive power supporting from the DSTATCOM is not enough. The sharing amount of reactive power compensation between DSTATCOM and capacitor banks can reduce the investment cost, which is good in term of economic, while the voltage control performance is still sufficient.

References

[1] Banerji A., Biswas S.K., Singh B. 2014. Enhancement Of Stability Of Autonomous Rural Grid, in *Control, Instrumentation, Energy and Communication (CIEC), 2014 International Conference on*, Calcutta, India. 462-466.

[2] BarghiLatran M., Teke A.,Yoldaş Y. 2015. Mitigation Of Power Quality Problems Using Distribution Static Synchronous Compensator: A Comprehensive Review. *Power Electronics, IET*. 8(7): 1312-1328.

[3] Sode-Yome A., Mithulananthan N. 2004. Comparison of Shunt Capacitor, SVC and STATCOM in Static Voltage Stability Margin Enhancement. *International Journal of Electrical Engineering Education.* 41(2): 158-171.

[4] Barlow M., The odoridis M., Bishop M.T. 2011. The Design Of Wind Plant Reactive Compensation System Alternatives To Meet Grid Code Requirements, in *Innovative Smart Grid Technologies (ISGT Europe), 2011 2ndIEEE PES International Conference and Exhibition on* 2011.

[5] Camm E.H., Behnke M.R., Bolado O., Bollen M., Bradt M., Brooks C., Dilling W., Edds M.,Hejdak W.J., Houseman D., Klein S., Li F., Li J., Maibach P., Nicolai T., Patino J., Pasupulati S.V., Samaan N., Saylors S., Siebert T., Smith T., Starke M., Walling, R. 2009. Reactive Power Compensation For Wind Power Plants. *Power & Energy Society General Meeting, 2009. PES '09. IEEE*

[6] Hofmann W.,Schlabbach J., Just W. 2012. *Reactive Power Compensation; A Practical Guide*, 1sted, Wiley.

[7] Noroozian M., Petersson N.A., Thorvaldson B., Nilsson B.A., TaylorC.W. 2003. Benefits of SVC and STATCOM for electric utility application. *Transmission and Distribution Conference and Exposition, 2003 IEEE PES*. 1143-1150

[8] Acha E.,Agelidis V., AnayaO., Miller T. 2002.*Power Electronic Control in Electrical Systems,*1sted, Newnes.

[9] Yazdani, A,Iravani, R. 2010. *Voltage-Sourced Converters in Power Systems*, 1sted, Wiley.

[10] DIgSILENTGmbh. 2013, *DIgSILENT Technical Documentation: PWM Converter*.DIgSILENT*PowerFactory* manual v.15.

[11] ABB. 2007. REF 542*plus*, Power Factor Controller: Application and Setting Guide [online]. From: https://library.e.abb.com/public/418efec857f459e2c12573af0049fc4d/appl_Ref542plus_PCF_756441_ENa.pdf [Accessed on 27 September 2015)

[12] Camm E., Edwards C.,Mattern K., Williams S. 2009. Dynamic Reactive Power Control For Wind Power Plants, *Techwindgrid'09 Grid Integration Seminar*

[13] Sharma, R., Singh, A., Jha, A.N. 2014. Performance Evaluation Of Tuned PI Controller For Power Quality Enhancement For Linear And Non Linear Loads. *Recent Advances and Innovations in Engineering (ICRAIE)*. 12-19.

[14] RezaeeJordehi A. 2015. Brainstorm optimisation algorithm (BSOA): An efficient algorithm for finding optimal location and setting of FACTS devices in electric power systems, in *International Journal of Electrical Power & Energy Systems*. 69: 132-138.