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A multifunctional DSTATCOM for power quality improvement

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Abstract: The distribution static compensator (DSTATCOM) is used for various purposes such as load balancing, harmonic rejection, and power factor correction (PFC) in power distribution networks. In unbalanced and polluted power systems, the classic definition of power factor cannot be used for PFC due to the existence of harmonics and negative sequence components in voltage and current waveforms. In this paper, PFC is performed using the IEEE power factor definition for harmonic and unbalanced environments. Moreover, the application of a proportional-resonant (PR) controller is proposed as an effective controller in the stationary frame for DSTATCOM performance improvement. The PR controller is used in the abc-frame for load balancing and is then compared theoretically and by simulation with the conventional PI controller, which has the main drawback of steady-state error when used in the stationary frame. To improve the DSTATCOM structure, an LCL harmonic filter is used as it is advantageous over the L/LC filter in terms of the size of the filter. The proposed DSTATCOM compensates for the disturbances in the source current imposed by nonlinear, unbalanced, and low power factor loads. Simulation results show the capability of the DSTATCOM including the proposed PR controller in improving the power quality of distribution systems.

Key words: Distribution static compensator, power quality, power factor (PF), harmonic suppression, load balancing, PR controller

1. Introduction

Nowadays, the rapid growth of power electronic devices and nonlinear and unbalanced loads has degraded the power quality of power distribution networks [1]. Moreover, a great portion of power consumption has been used by reactive loads, such as fans and pumps. Such loads draw lagging power factor currents and, thus, give rise to reactive power consumption in the distribution system. This situation becomes even worse in the presence of unbalanced loads. Excessive reactive power demand increases the ohmic losses and reduces the active power flow capability of the distribution system, whereas voltage unbalance has an adverse impact on the operation of transformers and generators [2]. To improve the quality of power, active power filters have been proposed [3–5]. To measure power quality, several standards such as IEEE 519-1992, IEEE Std. 141-1993, and IEC 1000-3-2, have been proposed [6–8].

The DSTATCOM is a shunt-connected compensator that injects currents into the distribution system through a current-controlled voltage-source inverter (VSI) [9–11]. The DSTATCOM is used for harmonic filtering, power factor correction, and load balancing. The VSI is used as an interface between a DC storage

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capacitor and the distribution system. The DSTATCOM performance is dependent on the control algorithm used to derive the reference current components. Several control schemes have been reported in the literature [12–21]. Genetic and fuzzy logic algorithms have been used to find the PI controller parameters of the DSTATCOM [12,13]. In [12] based on the error and its variation, a segmented PI strategy is presented. Utilization and selection of the proposed strategy have been performed according to fuzzy rules. An adaptive control strategy for the DSTATCOM on the basis of artificial immune system (AIS) is presented in [14]. This method uses the particle swarm optimization algorithm to obtain the optimal parameters of the controller. The controller parameters are adaptively adjusted when unknown and random disturbances are imposed on the system. The method also provides adaptive immunity for the control system. The aforementioned references do not consider power factor correction, harmonic suppression, or load balancing.

A neural network (NN)-based control algorithm for a 3-phase 4-wire DSTATCOM is proposed in [15]. The method compensates for the load current harmonics and zero-sequence current, balances the load voltage, regulates the voltage, and controls the power factor. In [16], a control algorithm based on the leaky least-mean-square method is proposed for a 3-phase DSTATCOM. The main advantage of the proposed control algorithm is that it has an improved dynamic response. Control algorithms based on an enhanced phase-locked loop (EPLL) scheme are also implemented for load balancing, reactive power compensation, and harmonic elimination in zero voltage regulation (ZVR) and PFC modes of operation of the DSTATCOM [17]. In such methods, the EPLL is used for harmonic and interharmonic estimation. A composite observer-based control algorithm is implemented in a 3-phase DSTATCOM for improving power quality, e.g., harmonic elimination, reactive power compensation, load balancing, and neutral current compensation in a 3-phase 4-wire distribution system [18–20]. In [21], a linear sinusoidal tracer control algorithm based on adaptive theory is used by a DSTATCOM for the extraction of fundamental components of load currents in 3-phase loads. Power factor correction and zero voltage regulation along with load balancing and harmonics elimination are carried out by the method. Good accuracy of detection, performance stability, and fast dynamic response are some of the advantages of the proposed control strategy. The aforementioned methods do not propose a general definition for power factor when the power system is polluted with harmonics and unbalanced conditions. Most existing methods use a rotating reference frame (dq-frame) for modeling and control of 3-phase systems. The dq-frame is advantageous as it converts the time-varying sinusoidal signals to the step-like signals, and, as a result, the use of a PI controller can eliminate the steady-state error and provides a good performance for the closed-loop system. Nevertheless, the dq-frame suffers from double-frequency ripples resulting from the unbalanced conditions.

To overcome the shortcomings of the existing methods, this paper employs a P+Resonant (PR) controller for power factor correction, DC-link voltage control, and load voltage balancing in the abc-frame. The PR controller is structurally simple and is used to eliminate the steady-state error when the reference signal is sinusoidal [22]. In the proposed scheme, in order to eliminate the current harmonics, the load current is fed to a low pass filter (LPF) and the output of the LPF is added to the reference signals generated by the other control blocks.

The paper is organized as follows. The general structure of the DSTATCOM is provided in Section 2. The basis of the proposed control method is described in Section 3. In Section 4, the inverter harmonic filter design is described. Finally, the simulation results are provided in Section 5, which show the effectiveness of the proposed control scheme for the DSTATCOM.

2. The DSTATCOM components

A typical DSTATCOM connected to a distribution system is shown in Figure 1. The DSTATCOM essentially consists of an injection transformer, an inverter output filter, a voltage source converter (VSC), and a DC-link capacitor. A VSC consisting of 12 switches (3 full H-bridge converters) is used to compensate for each phase individually. In fact, the VSC performs as 3 single-phase converters so that it can cope with zero sequence currents under unbalance conditions. The VSC generates some high-frequency harmonics due to the switching function. Thus, a filter is used to eliminate the high-frequency harmonics. In this paper, an LCL filter is used for this purpose. Most existing methods use a simple first-order L filter. However, the series L filter is usually bulky and inefficient. The LCL filters can meet the grid interconnection standards at a smaller size and lower cost. Design of the LCL filter will be explained in section 4.

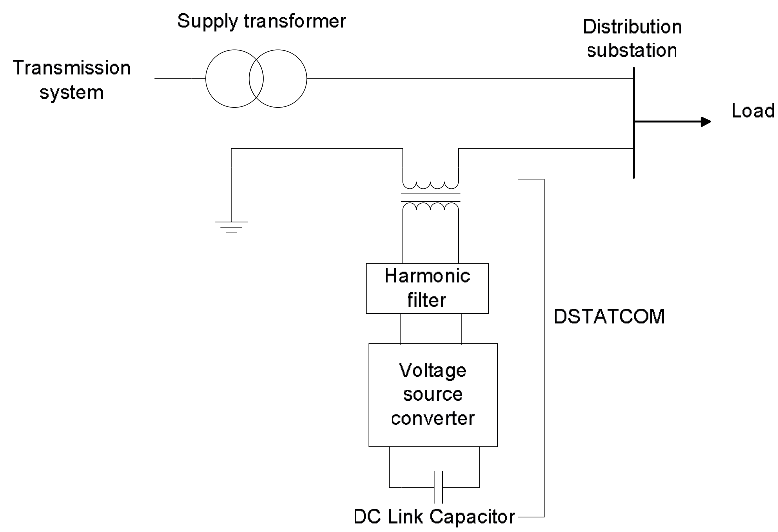

Figure 1. The distribution system with the DSTATCOM.

3. The control algorithm for the proposed DSTATCOM

3.1. The definition of power factor in harmonic and unbalanced environments

In this section, to define power factor under harmonic and unbalanced conditions, we adopt IEEE std 1459-2010 [23]. The harmonic components of voltages and currents are extracted using low-pass and band-pass filters. Suppose that the system is polluted with dominant harmonics of 2nd, 3rd, 5th, and 7th order. After extracting the harmonic components, the positive-, negative-, and zero-sequence of the fundamental component of the signal expressed by Eq. (1) is extracted as in [24]:

$$u_1^+(t) = \frac{1}{3}\left\{u_{a1}(t) + u_{b1}(t - \frac{2}{3}T) + u_{c1}(t - \frac{1}{3}T)\right\} \tag{1}$$

$$u_1^-(t) = \frac{1}{3}\left\{u_{a1}(t) + u_{b1}(t - \frac{1}{3}T) + u_{c1}(t - \frac{2}{3}T)\right\}$$

$$u_1^0(t) = \frac{1}{3}\left\{u_{a1}(t) + u_{b1}(t) + u_{c1}(t)\right\},$$

where “T” is the period of signal “u”. Subscripts “a”, “b”, and “c” represent phases, and subscript “1” denotes the fundamental component. Moreover, the superscripts “+”, “–”, and “0” represent positive-, negative- and zero-sequence, respectively. The fundamental component of active power (P_1^+) for positive-sequence can be computed as

$$P_1^+ = 3V_1^+ I_1^+ \cos\phi_1^+, \tag{2}$$

where V_1^+ and I_1^+ are the fundamental components of positive-sequence of voltage and current, respectively, and φ_1^+ is the phase difference between them. The total apparent power (S_e) will be as follows:

$$S_e = 3V_e I_e, \tag{3}$$

where V_e and I_e are the equivalent voltage and current, respectively, and are expressed as follows:

$$V_e = \sqrt{V_{e1}^2 + V_{e2}^2 + V_{e3}^2 + V_{e4}^2 + V_{e5}^2 + V_{e7}^2} \tag{4}$$

$$I_e = \sqrt{I_{e1}^2 + I_{e2}^2 + I_{e3}^2 + I_{e4}^2 + I_{e5}^2 + I_{e7}^2}$$

In (4), V_{e1} and I_{e1} are the fundamental components of the equivalent voltage and current, and are derived as follows:

$$V_{e1} = \sqrt{\left(\frac{V_{a1}^2 + V_{b1}^2 + V_{c1}^2}{6} + \frac{V_{ab1}^2 + V_{bc1}^2 + V_{ca1}^2}{18}\right)} \tag{5}$$

$$I_{e1} = \sqrt{\frac{I_{a1}^2 + I_{b1}^2 + I_{c1}^2}{3}} \tag{6}$$

Thus, the power factor (PF) under harmonic and unbalanced conditions is defined as

$$PF = P_1^+ / S_e \tag{7}$$

3.2. The proposed control algorithm for DSTATCOM

Figure 2 shows a block diagram of the proposed control strategy for compensation of harmonics, unbalance, and power factor. The proposed control scheme consists of 3 control loops: power factor correction loop (part (a)), load balancing loop (part (b)), and part (c), which compensates for harmonics and determines the final reference signal for DSTATCOM. The outputs for the control loops of parts "a" and "b" have the main frequency (i.e. 50 Hz), but the one for part "c" has the frequency components that should be compensated.

As seen from Figure 2a, PF is computed according the definition given in IEEE std 1459-2010, i.e. Eqs. (1)–(7) are used to determine the PF. Then the error signal between the PF and its reference value is applied to "P+Resonant controller 1" block to derive the q-axis component of the DSTATCOM fundamental component injection current, which is needed to provide reactive power that is sufficient for the PF correction. The PR controller [22] eliminates the steady-state error and meets the prespecified performance criteria. The transfer function of an ideal PR controller is:

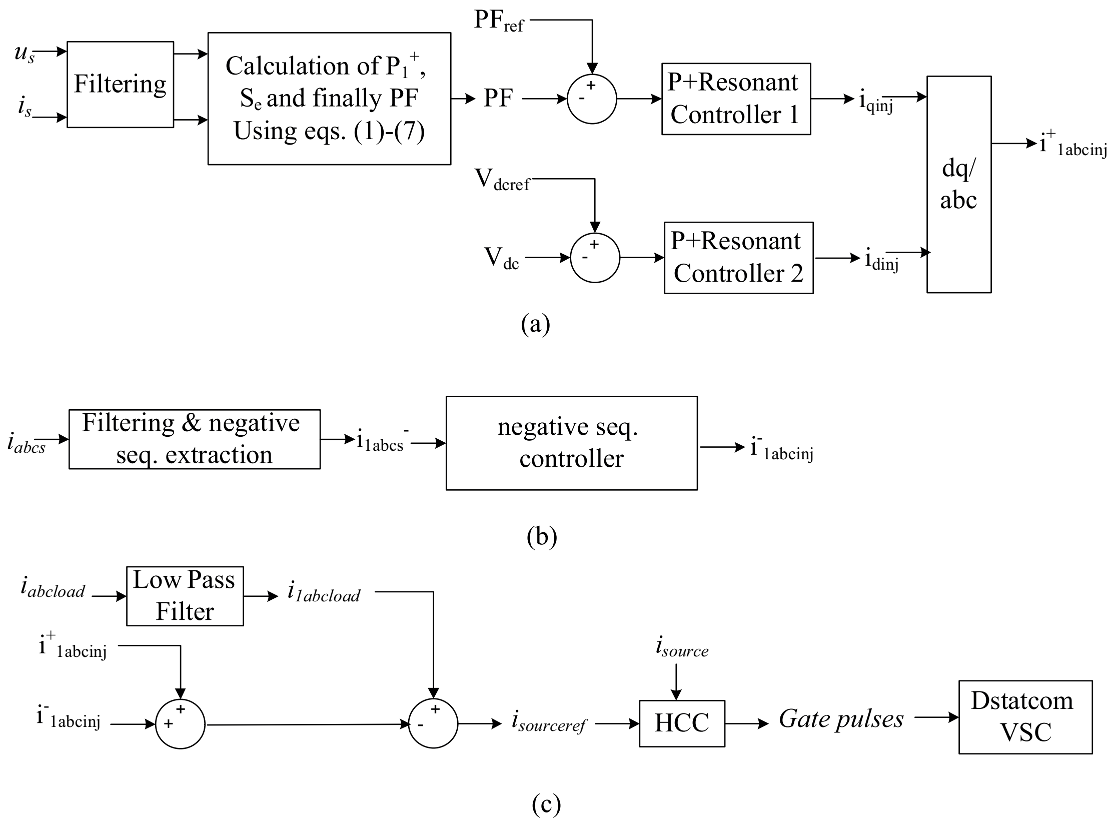

Figure 2. The DSTATCOM control block diagram. (a) power factor correction (b) load balancing (c) harmonic rejection.

$$G_R(s) = k_p + \frac{2k_I S}{S^2 + \omega_0^2}, \tag{8}$$

where k_P and k_I are the proportional and resonant gains, respectively, and ω_0 is the resonant frequency of the PR controller. The resonant controller introduces an infinite gain at the resonant frequency ω_0 to eliminate the steady-state error of the voltage. It is to be noted that an infinite gain is not attainable in practice. Therefore, the following realizable transfer function is used:

$$G_R(s) = k_p + \frac{2k_I \omega_{cut} S}{S^2 + 2\omega_{cut} S + \omega_0^2}, \tag{9}$$

where ω_{cut} is the compensator cut-off frequency and is set to 0.5 rad/s for this application. The bode plots of the PR controllers are given in Figure 3. As it is observed, the magnitude plot rolls off after the cut-off frequency. To regulate the DC-link voltage and to compensate for the PF, ω_0 is set to zero in the PR controller. Moreover, to eliminate the negative-sequence of the current, ω_0 in the PR controller is set to 314 (i.e. $2\pi f$ with $f = 50$ Hz).

The PR controller presents better performance as compared to a PI one when the system is modeled in the synchronous reference frame and therefore the reference signals are sinusoidal. Hence the previously known shortcomings associated with conventional PI controllers, such as the presence of steady-state error in the stationary frame and the need to decouple phase dependency in 3-phase systems, can be alleviated.

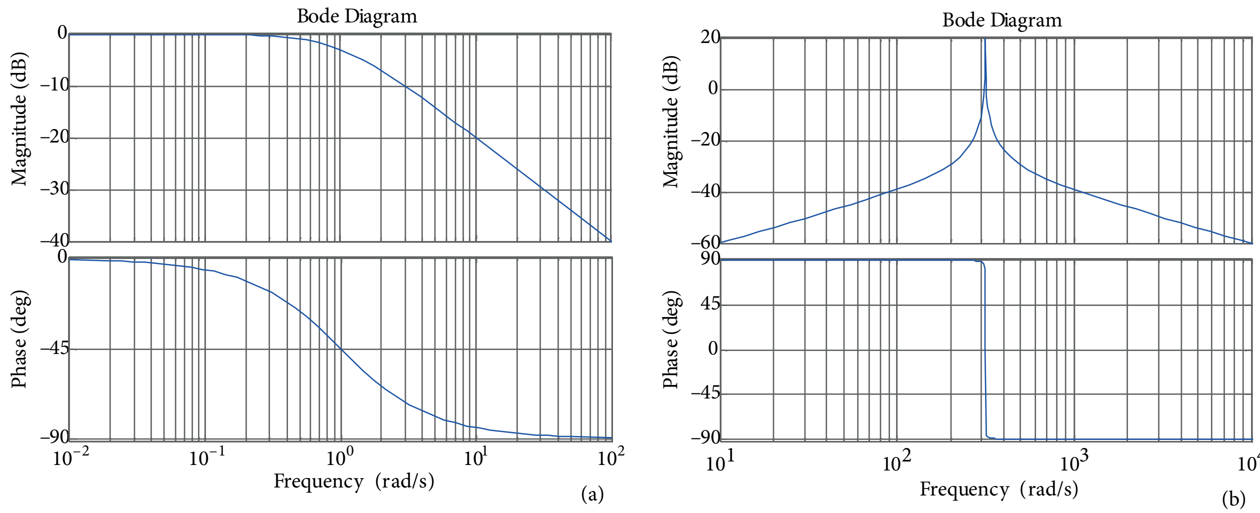

Figure 3. The bode plots of (a) P+Resonant1 and P+Resonant2, (b) P+Resonant3 whose parameters are given in the appendix.

As observed from Figure 2a, the voltage of the DC-link capacitor is regulated using the d-axis component of the DSTATCOM fundamental component injection current, which is needed to provide active power that is sufficient for the DC-link voltage regulation. The reference of DC-link voltage is set to 15 kV.

To balance the load voltage, the negative-sequence of the fundamental component of the source current is first extracted (Figure 2b). It is then applied to the negative-sequence control block. The details of the negative-sequence control loop are shown in Figure 4. As can be seen, the PR controller is incorporated in the synchronous reference frame and the negative sequence signals, which should be compensated, are sinusoidal. Hence, there is no need to decouple phase dependency.

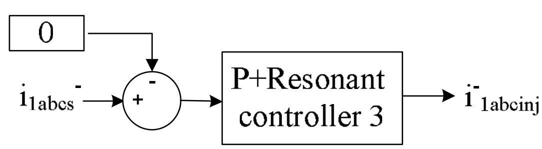

Figure 4. Load balancing control block.

To determine the reference signal $i_{sourceref}$ in Figure 2c, the currents required for PF compensation and the currents injected by the DSTATCOM for load balancing are subtracted from the fundamental component of the load current. The reference signals $i_{sourceref}$ and i_{source} are applied to the hysteresis current control (HCC) block. Finally the gating signals are produced by the HCC block and are fed to the DSTATCOM inverter (Figure 1).

4. Harmonic filter design

The DSTATCOM injects undesirable harmonics into the grid. Hence, the design of an appropriate filter to effectively attenuate such high-frequency switching harmonics is of paramount importance. Most existing DSTATCOMs proposed in the technical literature use a simple first-order L filter. However, the L filter is bulky and inefficient, and does not meet the specified requirements for the switching ranges of mid- to high-power inverter applications. Therefore, in this paper, an LCL filter is adopted in order to meet the grid interconnection standards at significantly smaller size and cost [25]. The per-phase equivalent circuit of an LCL filter is shown in Figure 5.

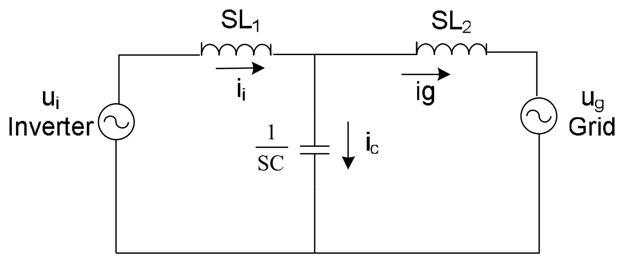

Figure 5. Single phase equivalent circuit of the LCL filter.

The inverter output voltage and current are represented by u_i and i_i, and the grid voltage and current are denoted by u_g and i_g, respectively. The switching frequency is f_{sw} (in Hz) or ω_{sw} (in radians per second). The grid is stiff enough such that it is considered an almost ideal voltage source. The transfer function of the LCL filter is

$$\left.\frac{i_g(s)}{u_i(s)}\right|_{u_g=0} = \frac{1}{S^3 L_1 L_2 C + S(L_1 + L_2)} \tag{10}$$

Eq. (11) determines the minimum value of $L = L_1 + L_2$ for which the IEEE 519-1992 standard recommendations are satisfied for current ripple at the switching frequency [25]. The size of L depends on the resonance frequency ω_r.

$$L = \frac{1}{\omega_{sw}\left|\frac{i_g}{u_i}\right|\left|1 - \frac{\omega_{sw}^2}{\omega_r^2}\right|} \tag{11}$$

$$L = \frac{1}{\omega_{sw}\left|\frac{i_g}{u_i}\right|\left|1 - \frac{\omega_{sw}^2}{\omega_r^2}\right|} \tag{12}$$

Now, using L and ω_r, the value of C is calculated from Eq. (13).

$$\omega_r^2 = 4/LC \tag{13}$$

According to (13), while ω_r is constant, the values of L and C can be adjusted if the computed L from (11) is very small and/or C $\geq$ 1 p.u. The response of the closed-loop system can be adjusted by the resonance frequency of the LCL filter. The closed-loop system will be unstable if some voltage/current harmonics coincide around the resonance frequency. To overcome this problem, a damping resistance is paralleled with the LCL filter capacitor [25]. The parameters of the designed LCL filter are given in Table 1. Figure 6 shows that the ratio of i_g to u_i is decreased when the switching frequency increases.

Table 1. Harmonic filter and dc-link capacitor parameters.

Parameter name	L_1 (mH)	L_2 (mH)	C (μF)	f_1 (Hz)	fr (Hz)	R_d (ohm)	C_{dc} (mF)
Value	20	1	25	50	1000	29	3

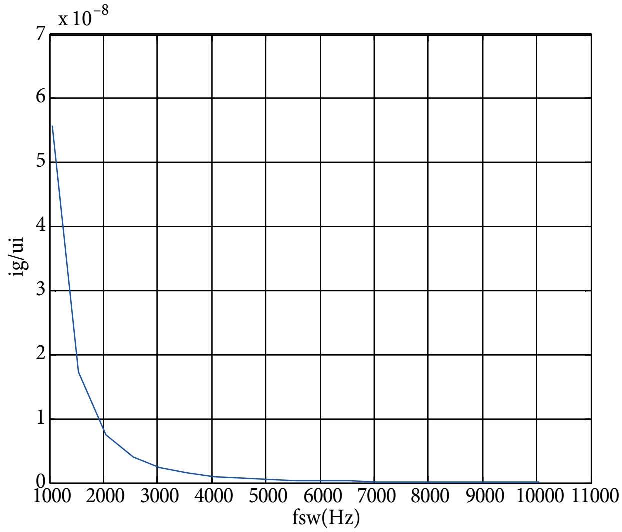

Figure 6. Variation of (i_g/u_i) with respect to f_{sw} for the filter parameters of Table 1.

The LCL filter is designed for high-power VSCs with the minimum switching frequency of 10 kHz. In the simulations, the IGBTs are used as the most suitable switching devices for such applications.

5. Simulation results and discussion

In this section, the performance of DSTATCOM including its proposed control algorithm is verified using simulation studies carried out in PSCAD/EMTDC software environment.

5.1. Test system

In this section, the IEEE standard 13-bus industrial system whose single-line diagram is depicted in Figure 7 is used as the test system.

The test system is implemented in PSCAD/EMTDC software. The control methods of Figure 2 and Figure 3 expressed by Eqs. (1)–(9) are employed to control the DSTATCOM. The DSTATCOM is a 12-pulse inverter whose phases can be controlled separately. Thus, the DSTATCOM acts as 3 single phase converters so that it can inject zero-sequence current.

The plant is fed from a utility supply at 69 kV and the local plant distribution system operates at 13.8 kV. The local (in-plant) generator is represented as a simple Thevenin equivalent circuit with the internal voltage of $13.8\ \angle -1.52^\circ$ kV, determined from the converged power flow solution. The equivalent impedance is the subtransient impedance and equals $0.0366 + j1.3651\ \Omega$. The plant power factor correction capacitors are rated at 6000 kVar. As is typically assumed, the leakage and series resistance of the bank are neglected in this study. A detailed description of the system is given in [26]. In the simulations, the DSTATCOM is connected to bus "05:FDR F". The whole DSTATCOM configuration, which is already used in PSCAD software, is also shown in Appendix 2.

5.2. Power factor correction, harmonic mitigation, and load balancing

In this part, 2 sets of loads are connected to bus "05:FDR F" in order to make some distortions in the feeder currents: 1. In 1 feeder, we have 3 single phase rectifiers each of which is connected to a parallel RC load

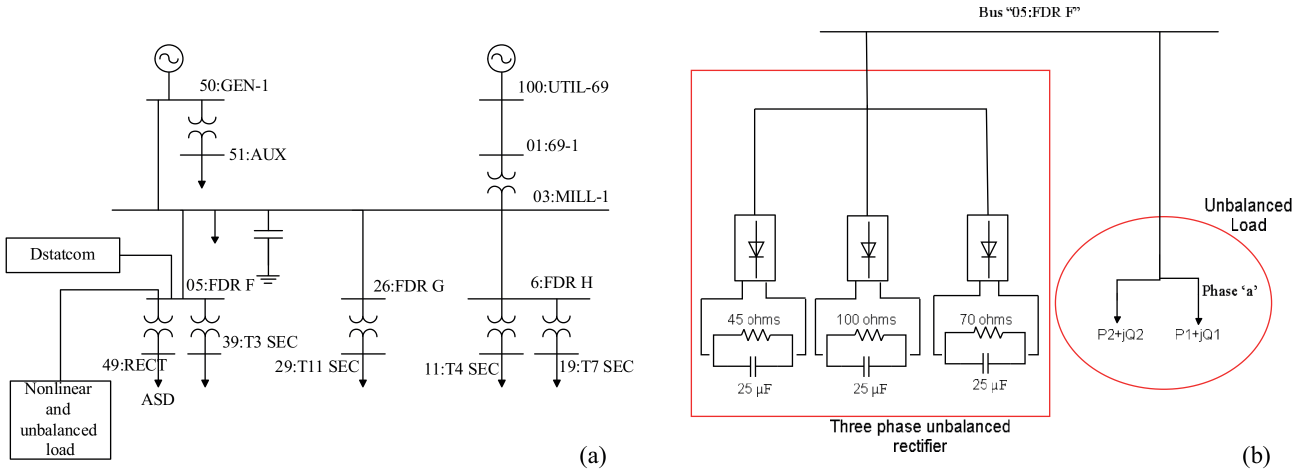

Figure 7. The under study test system (a) the overall view of system [26], (b) the "Nonlinear and unbalanced load" explanation.

with $R_a = 70\ \Omega$, $R_b = 100\ \Omega$, $R_c = 45\ \Omega$, $C_a = C_b = C_c = 25\ \mu$F; 2. In the other feeder, we have a 3-phase unbalanced constant power load of Sa = (0.01 + j3) MVA, Sb = 0, and Sc = (0.01 + j2) MVA. The current of the feeder between buses "03:MILL-1" and "05:FDR F" is shown in Figure 8a. Figure 8b shows the current waveforms after connecting the DSTATCOM to bus "05:FDR F". As can be clearly seen, the DSTATCOM has made the current waveforms smooth and balanced. The DSTATCOM injected currents are shown in Figure 8c. Part (d) in Figure 8 shows the result when a PI controller is used for load balancing (block diagram of Figure

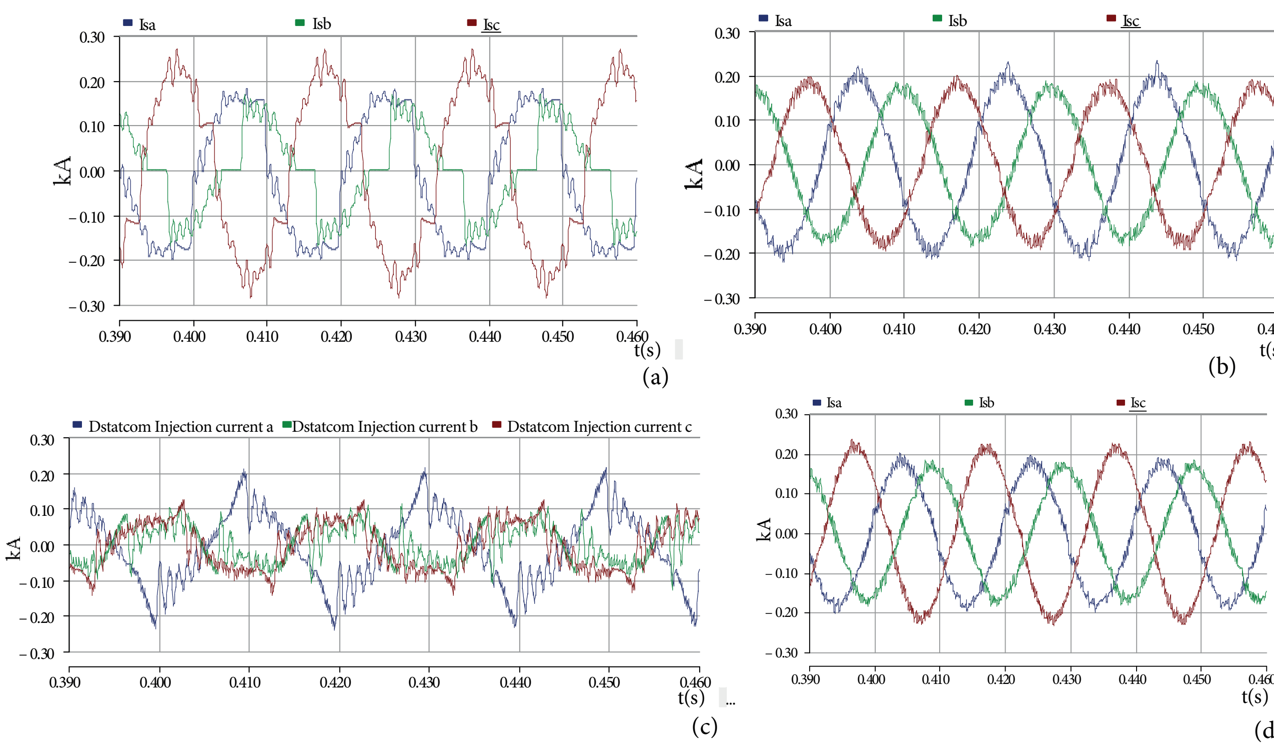

Figure 8. The source (a) distorted and (b) compensated currents, (c) the DSTATCOM injected currents, and (d) compensated currents when PI controller is used.

4). Comparison of parts (b) and (d) shows the effectiveness of the PR controller over the PI one. It is seen that the PR controller is more precise and effective. The PI parameters are given in Appendix 1. Tables 2–4 are also useful to show the superior performance of the DSTATCOM.

The harmonic spectrum of phase 'a' of the source current before and after compensation is shown in Figure 9. In this figure, all harmonics up to the order 31 are shown. The amplitudes of harmonics are less than 3.5 A while the amplitude of fundamental component is about 200 A. The current THD for each phase before and after compensation is given in Table 2. The THD is significantly decreased when the DSTATCOM is in service.

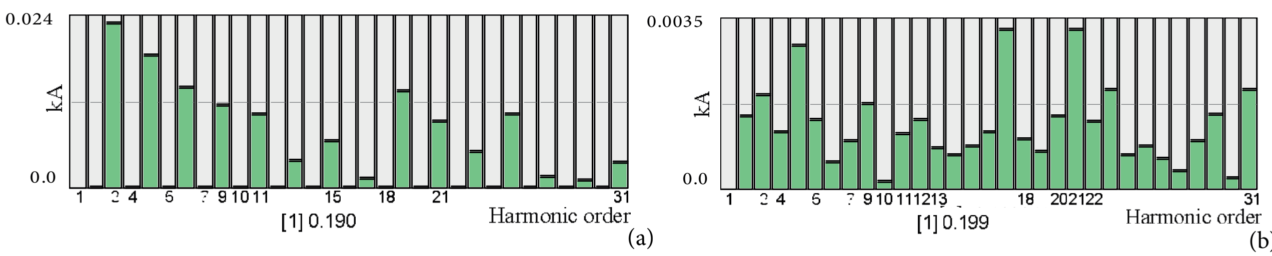

Figure 9. The harmonic spectrum of phase 'a' source current (a) before and (b) after compensation.

Table 2. Total harmonic distortion of each phase current before and after compensation.

	%THD before compensation	%THD after compensation
Phase a	21.7	5.83
Phase b	36.5	6.88
Phase c	16.5	6.52

The results of Table 3 validate the capability of the DSTATCOM in load balancing. The imbalance factor is defined as the ratio of the amplitude of negative-sequence to the amplitude of positive-sequence [24]. The imbalance factor for a specified harmonic component is defined as the ratio of the amplitude of negative-sequence of a given harmonic to the amplitude of positive-sequence of the fundamental component. As can be seen in Table 3, the current imbalance factor for the crucial harmonics is well below when the proposed DSTATCOM is used.

Table 3. Index of unbalance for each order of current harmonics.

Harmonic order (h)	1	3	5	7
Before compensation (%)	47.49	2.15	10.06	0.96
After compensation with PR controller (%)	0.67	1.32	1.12	0.42
After compensation with PI controller (%)	24.67	0.7	1.5	0.6

As discussed in section 1, the classic power factor definition cannot be used under harmonic and unbalanced systems conditions. For example, as shown in Table 4, the PF is 97% for the uncompensated source currents according to its classic definition whereas it is 86% if the IEEE std 1459-2010 is used.

Table 4. The power factor value before and after compensation.

	Before compensation	After compensation
Classic definition of PF	97%	99%
IEEE std 1459-2010 definition of PF	86%	99%

Figure 10 shows the voltage and current of phase "a" before and after compensation. In order to better compare the voltage and current waveforms in the same figure, the voltage has been scaled down to 5% of its original magnitude. As observed from Table 4 and Figure 10b, the power factor is increased to 99% and therefore the load current and voltage waveforms are almost in-phase.

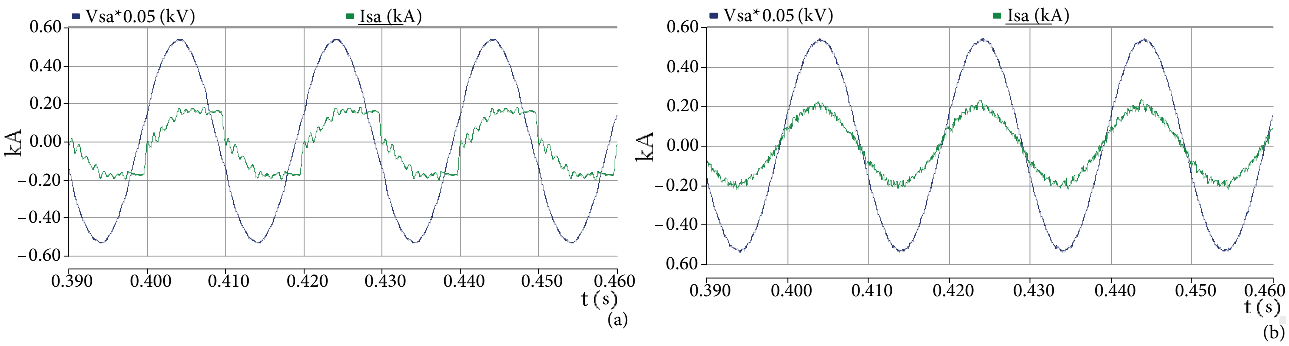

Figure 10. Voltage and current of phase A: (a) without DSTATCOM compensation, (b) with DSTATCOM compensation.

Thus in this paper a PR controller was designed and compared to the conventional PI controller. Moreover, power factor correction was performed when the power system is under harmonic and unbalanced conditions. An LCL harmonic filter was used as it is advantageous in terms of size, cost, and performance compared to its L or LC counterparts. The proposed DSTATCOM including its control algorithm was simulated in PSCAD/EMTDC software for various scenarios, e.g., compensation of harmonics resulting from nonlinear loads, load balancing, and power factor corrections. As compared to the PI controller, the performance of the proposed control strategy is significantly improved by employing the PR controller. Simulation results confirm the capability of the presented DSTATCOM in improving the power quality of distribution systems.

6. Conclusion

This paper presents a new control strategy for a DSTATCOM to overcome the power quality issues, e.g., harmonics and unbalance conditions. In particular, a PR controller is designed and compared to the conventional PI controller. Moreover, power factor correction is performed when the power system is under harmonic and unbalanced conditions. An LCL harmonic filter is used as it is advantageous in terms of size, cost, and performance compared to its L or LC counterparts. The proposed DSTATCOM including its control algorithm is simulated in PSCAD/EMTDC software for various scenarios, e.g., compensation of harmonics resulting from nonlinear loads, load balancing, and power factor corrections. As compared to the PI controller, the performance of the proposed control strategy is significantly improved by employing the PR controller. Simulation results confirm the capability of the presented DSTATCOM in improving the power quality of distribution systems.

References

[1] Bollen M. Understanding Power Quality Problems: Voltage Sags and Interruptions. New York, NY, USA: IEEE Press, 1999.

[2] Moreno-Munoz A. Power Quality: Mitigation Technologies in a Distributed Environment. London, UK: Springer-Verlag, 2007.

[3] Ucar M, Ozdemir S, Ozdemir E. A four-leg unified series–parallel active filter system for periodic and non-periodic disturbance compensation. Electr Pow Syst Res 2011; 815: 1132-1143.

[4] Chaoui A, Gaubert JP, Krm F. Power quality improvement using DPC controlled three-phase shunt active filter. Electr Pow Syst Res 2010; 806: 657-666.

[5] Kale M, Ozdemir E. A new hysteresis band current control technique for a shunt active filter. Turk J Elec Eng & Comp Sci 2015; 23: 654-665.

[6] IEEE Std 519. IEEE Recommended Practices and Requirements for Harmonics Control in Electric Power Systems, 1992.

[7] IEEE Std 1159. IEEE Recommended Practice for Monitoring Electric Power Quality, 1995.

[8] IEEE Std 1531. IEEE Guide for Application and Specification for Harmonic Filters, 2003.

[9] Rahbarimagham H, Maali Amirie E, Vahidi B, Babamalek Gharehpetian G, Abedi M. Superior decoupled control of active and reactive power for three-phase voltage source converters. Turk J Elec Eng & Comp Sci 2015; 23: 1025-1039.

[10] Mokhtari M, Khazaei J, Nazarpour D, Farsadi M. Interaction analysis of multifunction FACTS and D-FACTS controllers by MRGA. Turk J Elec Eng & Comp Sci 2013; 21: 1685-1702.

[11] Anadol MA, Aydın M, Yalçınöz T. A real-time extraction of active and reactive current using microcontrollers for a multipulse STATCOM. Turk J Elec Eng & Comp Sci 2013; 21: 1044-1060.

[12] Jazebi S, Hosseinian SH, Vahidi B. DSTATCOM allocation in distribution networks considering reconfiguration using differential evolution algorithm. Energ Convers Manage 2011; 52: 2777-2783.

[13] Valderrabano A, Ramirez JM. DSTATCOM regulation by a fuzzy segmented PI controller. Electr Pow Syst Res 2010; 80: 707-715.

[14] Mitra P, and Venayagamoorthy GK. An adaptive control strategy for DSTATCOM applications in an electric ship power system. IEEE Power Electron 2010; 25: 95-104.

[15] Singh B, Jayaprakash P, Kumar S, Kothari DP. Implementation of neural-network-controlled three-leg VSC and a transformer as three-phase four-wire DSTATCOM. IEEE Ind Applic 2011; 47: 1892-1901.

[16] Arya SR, Singh B. Performance of DSTATCOM using leaky LMS control algorithm. IEEE J Sel Top Power Electron 2013; 1: 104-113.

[17] Singh B, Arya SR. Implementation of single phase enhanced phase-locked loop based control algorithm for three phase DSTATCOM. IEEE T Power Deliver 2013; 28: 1516-1524.

[18] Selvajyothi K, Janakiraman PA. Analysis and simulation of single phase composite observer for harmonics extraction. In: IEEE 2006 International Conference on Power Electronic Drives and Energy Systems; 12–15 Dec 2006; New Delhi: IEEE. pp. 1-6.

[19] Selvajyothi K, Janakiraman PA. Extraction of harmonics using composite observers. IEEE T Power Deliver 2008; 23: 31-40.

[20] Singh B, Arya SR. Composite observer-based control algorithm for distribution static compensator in four-wire supply system. IET Power Electron 2013; 6: 251-260.

[21] Singh B, Arya SR. Adaptive theory-based improved linear sinusoidal tracer control algorithm for DSTATCOM. IEEE Power Electron 2013; 28: 3768-3778.

[22] Mahdianpoor M, Hooshmand R, Ataei M. A new robust approach to multifunctional dynamic voltage restorer implementation for emergency control in distribution systems. IEEE T Power Deliver 2011; 26: 882-890.

[23] Emanuel A. Power Definitions and the Physical Mechanism of Power Flow. 1st ed. Chichester, UK: Wiley-IEEE Press, 2010.

[24] Bollen MJ. Signal processing of power quality disturbances. Chichester, UK: Wiley-IEEE Press, 2006.

[25] Parikshith C, Vinod J. Filter Optimization for Grid Interactive Voltage Source Inverters. IEEE T Ind Electron 2010; 57: 4106-4114.

[26] Task Force on Harmonics Modeling & Simulation (co-author). Test Systems for Harmonics Modeling and Simulation. IEEE T Power Deliver 1999; 14: 579-85 (SCI, EI).

Appendices

Appendix 1. P+Resonant and PI controller parameters

The parameters of the 3 PR controllers given in Figures 2 and 3 are as follows. The cut-off frequency for all PR controllers, ω_{cut}, is set to 0.5 rad/s. ω_0 is set to zero for P+Resonant1 and P+Resonant2, and it is set to 314 for P+Resonant3. Parameter k_p is set to zero in all 3 controllers. The value of k_i is set to 1 in P+Resonant controller 1 and 2 and is set to 10 in P+Resonant3. In the case of the PI controller, k_p is set to 1 and k_i is set to 10.

Appendix 2. The PSCAD model for DSTATCOM structure and controllers

Figure 11 shows the DSTATCOM model used in simulations and Figure 12 shows the control blocks.

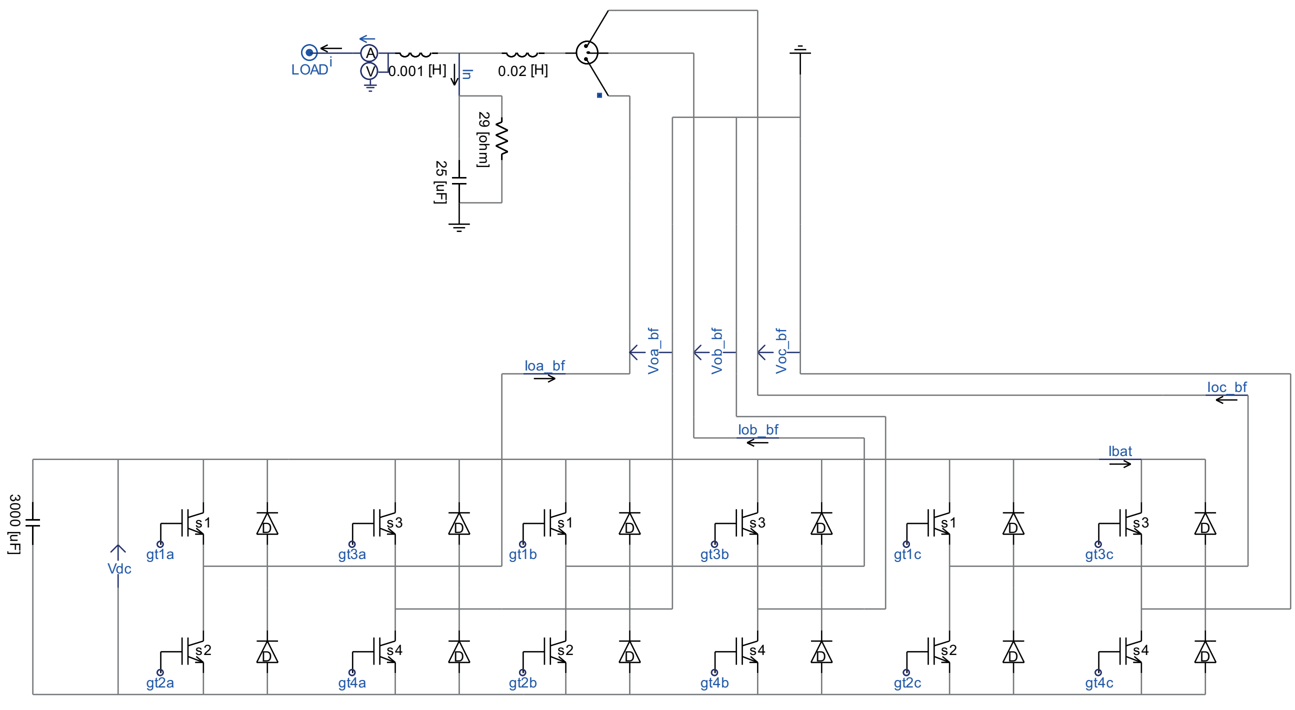

Figure 11. The DSTATCOM model used in simulations.

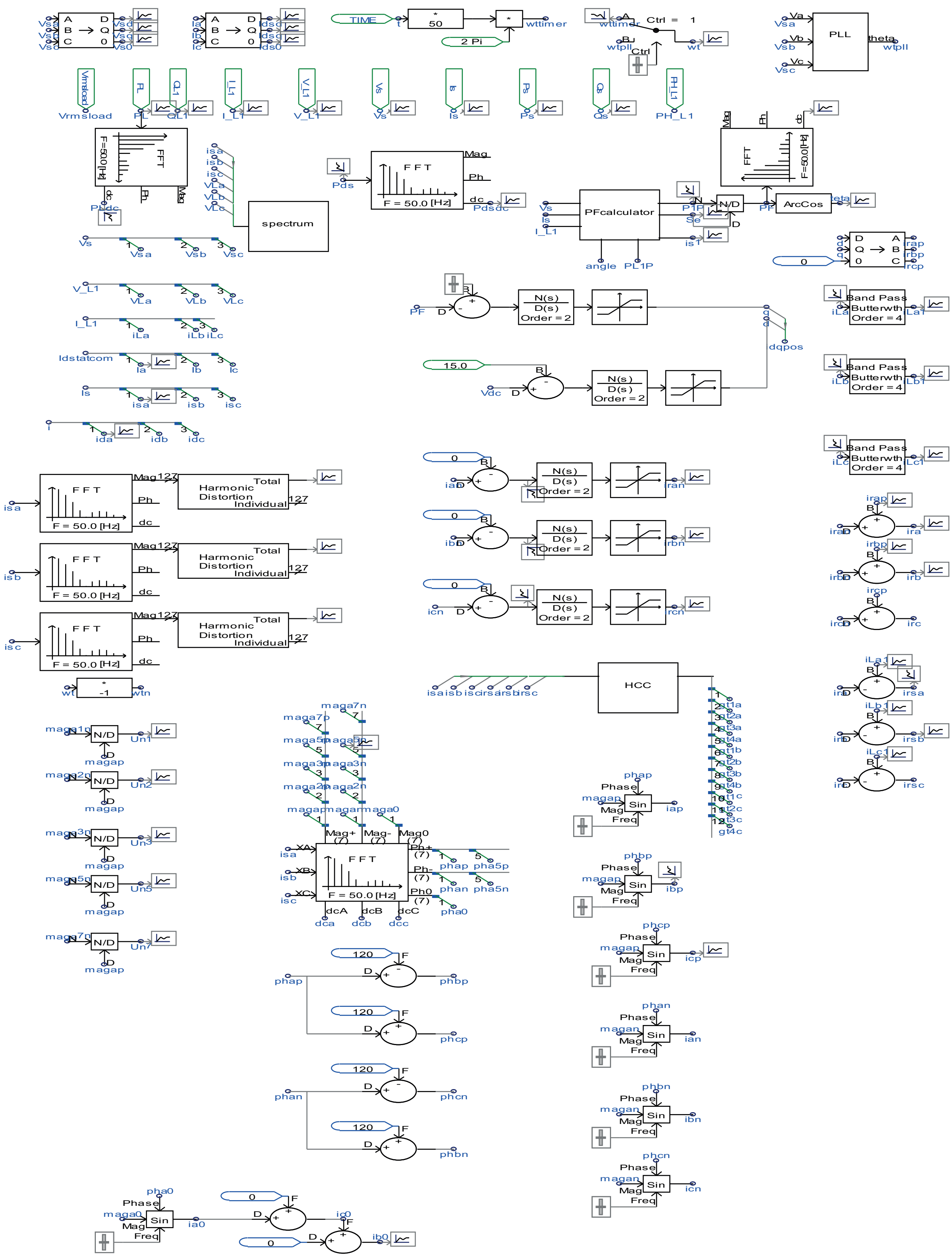

Figure 12. The DSTATCOM control blocks.