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Power Quality Improvement in Microgrids using STATCOM under Unbalanced Voltage Conditions

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A B S T R A C T

A large number of single-phase loads and sources create unbalanced voltage in microgrids. Voltage unbalance reduces the power quality, which results in misoperation or failure of customer equipment and microgrid. Also, voltage unbalance negatively impacts induction motors, power electronic converters, and adjustable speed drives. Static synchronous compensator (STATCOM), as an influential segment of the Flexible Alternative Current Transmission Systems (FACTS), has been extensively utilized as shunt compensators for controlling reactive power and regulation voltage in transmission and distribution networks. Under unbalanced conditions, an oscillating couple between the positive and negative sequence components of control loops emerge in the d-q frame. This paper suggests an innovative point of common coupling (PCC) voltage controller in Decoupled Double Synchronous Reference Frame (DDSRF) to compensate for an unbalanced PCC voltage and reduce the oscillating couple using STATCOM. Implementation of the proposed DDSRF involves several steps. Firstly, unbalance signals are rotated counterclockwise to split up the positive sequences. Secondly, those signals are rotated clockwise to separate negative sequences. Finally, by utilizing mathematical equations, the proposed DDSRF is introduced, which enables independent control of positive and negative sequence components. This study controls DC capacitor voltage for unbalanced conditions. Furthermore, the regulation voltage at PCC is performed. The control system scheme is also designed under unbalanced conditions, and simulation results guarantee the suggested control strategy.

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NOMENCLATURE

V_{sabc}	Line to neutral voltages at the PCC.	$v^{-}_{sqd\_ref}$	Negative sequence d-q components of the voltage reference.
I_{abc}	Line currents supplied by the VSC.	P^{+}, Q^{+}	Positive sequence active and reactive power.
v^{+}_{sqd}	Positive sequence d-q components of the voltage at the PCC.	L, R, C_f	Output filter of the DG.
v^{-}_{sqd}	Negative sequence d-q components of the voltage at the PCC.	k^{+}_{qdv}	Proportional controller of the positive inner voltage loop.
v^{+}_{tqd}	Positive sequence d-q components of the voltage at DG terminal.	k^{-}_{qdv}	Proportional controller of the negative inner voltage loop.
v^{-}_{tqd}	Negative sequence d-q components of the voltage at DG terminal.	k^{+}_{qdI}	Proportional integral controller of the positive inner current loop.
i^{+}_{qd}	Positive sequence d-q components of the current.	k^{-}_{qdI}	Proportional integral controller of the negative inner current loop.
i^{-}_{qd}	Negative sequence d-q components of the current.	τ_i	Time constant of the closed loop current control.
i^{+}_{lqd}	Positive sequence d-q components of the load current.	Z_L	Line impedance.
i^{-}_{lqd}	Negative sequence d-q components of the load current.	C	DC-side capacitor.
$i^{+}_{qd\_ref}$	Positive sequence d-q components of the reference current.	V_{dc_ref}	References of DC voltage.
$i^{-}_{qd\_ref}$	Negative sequence d-q components of the reference current.	V_{dc}	Output of DC voltage.
$\theta^{\pm}$	Positive and negative sequence of the angle.	K_{vdc}	DC-bus compensator.

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$\varphi^{\pm}$	Positive and negative sequence of the initial phase.	V_g	Grid voltage.
ω_n, ξ	Natural frequency and damping ratio of notch filter.	PLL	Phase locked loop.
$v^{+}_{sqd\_ref}$	Positive sequence d-q components of the voltage reference.	PCC	Point of common coupling.

1. INTRODUCTION

In this energy-oriented era, the concept of the microgrid is of great significance. The microgrid is a power generation system with distributed generation units (DGs), loads, and energy storage systems. Although microgrids can be utilized in grid-connected mode, they also must have the capability to operate in islanding mode [1-2]. Amongst the various uncertainties of microgrids, the power quality problem is essential. One of the most challenging issues that put the power quality at high risks is voltage unbalance that may cause detrimental effects on equipment like transformers and induction motors [3]. Unbalanced voltage occurs because of the existence of unbalanced loads such as single-phase loads. Under unbalanced voltage conditions, microgrids can compensate for the unbalances so that the power delivered to sensitive loads at the PCC does not experience the quality reduction.

Accordingly, new systems are introduced to handle such obstacles and, consequently, improve the power grids performance. Flexible Alternative Current Transmission Systems (FACTS) devices are possible solutions to the above-mentioned issues. If FACTS devices are used beside proper controllers, they can enhance active and reactive power quality [4]. A static synchronous compensator (STATCOM) is a shunt FACTS device that exceedingly prominent in the power applications and voltage regulation of the PCC, and it can be employed to compensate for the unbalanced voltage [5]. To regulate the voltage at the point of common coupling (PCC), the STATCOM device controls reactive power volume. When the grid voltage is lower than what is needed, the STATCOM generates reactive power to increase the voltage. On the converse, when the system's voltage is higher than anticipated, it consumes the correct sum of reactive power to diminish the voltage [6].

In the structure of STATCOMs, voltage source converters (VSCs) are used. Considering this feature, the extra capacity of the control system of VSCs for injecting active and reactive power, voltage balancing and power quality improvement can be applied [7]. Properly injecting the power is one of the essential roles of the control system. To achieve this goal, DC-link control must be investigated. Hysa [8] used a PV system to produce power in DC side of the microgrid. Moreover, the effects of series and parallel resistances in the PV output are measured. However, the main point is to control the DC-link and how to consume this power. The feedback on controlling injected power was not provided by Hysa [8]. Besides, energy storage systems and secondary batteries are considered by Slavova et al. [9] and Sani [10], respectively. As it has already been mentioned, in previous studies, DC-link power port control was not investigated. Hence, a storage system and a PV were combined to build a microgrid [11]. AC and DC load are fed by this collection, and the main purpose of this microgrid is to control the DC port by using a PID controller. However, it should be noted that the controllers by Sagar and Debela [11] are designed in balanced conditions and without any fluctuations. It has got merit to be mentioned that under unbalanced conditions, storage systems and batteries performance are disrupted. Consequently, using a control system to cope with unbalanced condition is necessary. Therefore, many different methods have been extended to compensate for the unbalanced voltage by STATCOMs in the literature, mainly based on the separation of positive and negative sequence components. A novel form of STATCOM was introduced by Somasundaram and Rajesh Babu [12] utilizing a matrix converter in the control system to compensate for unbalanced voltage. In this method, to achieve robust performance, Particle Swarm Optimization was also added to the control system. Nevertheless, this approach eliminated dc port control, and there is no discussion of how active power is controlled because we know that the DC-link must be controlled to control the active power. It was also not a matter of separation of the asymmetric components of unbalancing. Song and Liu. [13] used the multi-level construction of STATCOM, which was star-connected to produce positive and negative components. But this approach was not appropriate for the multi-level STATCOM, and the implementation algorithm was very complicated. One strategy for unbalanced voltage compensation in STATCOMs can be based on microgrid modeling under the three-phase (Abc) frame. The dynamic phasor (DP) technique is an averaging method, which describes a time-domain waveform using DC variables [14]. That means a balance could be achieved from the dynamic phasor model in the (Abc) reference frame. A dynamic phasor concept has been presented by Shuai et al. [15] to model the unbalanced microgrid, including inverters. This dynamic phasor model has been developed in the (Abc) reference frame while the inner control loops of current and voltage have been studied through the rotating d-q coordinate.

On the other hand, some studies have proposed the Double Synchronous Reference Frame (DSRF) structure in the control system. In this method, to separate the positive and negative sequence components, the unbalanced signals (voltage/current) are rotated counterclockwise with the system angular frequency. Doing this, 2W frequency oscillation emerges in the d-q frame. Since PI controllers are used in the inner control loops of DGs [16], oscillations with 2W frequency lead to some perturbations in the DG operation and affect the voltage control of the DC-link. Therefore, filters are applied to eliminate these oscillations [17-18]. A notch filter in the STATCOM control system was considered by Zhenglong et al. [19] to compensate the unbalanced voltage. However, the implementation of these methods cannot delete the oscillations between positive and negative components as well as the d-q frame, and it results in weakening the performance of the control system. Consequently, the DDSRF structure was suggested to remove the oscillating couple. The small-signal model of the DDSRF structure was proposed [20]. The DDSRF construction was exploited in the control system in which the current references were assumed to be completely DC and did not include oscillating components [21-22]. In fact, the current references have oscillating terms and they must be removed. Therefore, in this paper, the modified DDSRF method is introduced in the STATCOM control system to virtually eliminate the oscillating couple between positive and negative components in a case of unbalancing. The simulation results show that the proposed control approach compared to the conventional method in literature [21-22] is much more reliable and cross-coupling term effectively damped. Furthermore, the unbalanced voltage at PCC is compensated, and the voltage unbalance factor is under limited value. Also, the control system is designed so that DC-link control is not impaired by unbalanced conditions and, on the other hand, controlling and balancing the voltage of PCC are done. Finally, reactive power injection is performed to control AC voltage via a control system based on modified DDSRF.

This paper is organized as follows. In the second section, the structure of DDSRF is described. Then, in the third section, the control system of the STATCOM is presented. In the fourth section, the results of simulation of the STATCOM are discussed. The general conclusion is summarized in section five.

2. METHOD

The main goals of this paper are voltage balancing at PCC with different DDSRF-based control structures and, of course, DC-link control in the presence of unbalanced conditions. Figure 1 presents the schematic of a STATCOM in the grid-connected mode with connecting unbalanced load using an LCL filter. Moreover, in this figure, the control system of STATCOM is illustrated. To separate the positive and negative sequence components, DDSRF is used. The voltage control loop for compensating receives the positive and negative components and generates the controlling commands of the reference current. After the generation of reference currents, the current control loop is used to control the VSC current. References voltages in negative sequence *d-q* frame, $v_{sdref}{}^{-}$ and $v_{sqref}{}^{-}$ are equal to zero and $v_{sdref}{}^{+}$ is equal to the amplitude of grid voltage, i.e., 391v. These assumptions are considered because, in the unbalanced condition, the magnitude of V_d^- and V_q^- has an accountable value, but these values are about zero in the balance condition. For the after-mention reason, we consider $V_{sdref}^- = V_{sqref}^- = 0$ and utilize a proper controller in the voltage loop to achieve this purpose. The same scenario can be said for V_{sdref}^+ because, in balanced conditions, the magnitude is equal to the grid voltage. That is why $V_{sdref}^+ = 391\,v$.

3. PROPOSED CONTROL SYSTEM OF STATCOM

3. 1. DDSRF Organization in STATCOM

The particular injection of negative and even the positive components of the current and voltage is vital to compensate for the unbalanced network; hence the negative and positive collection elements must be separated, which can be utilized for DSRF. In this technique, to split up the positive aspect, the current/voltage signal must turn counterclockwise. Furthermore, for any separation with the negative component, the current/voltage signal should be rotated within the clockwise direction. So, the three-phase unbalance current is considered as follows [23]:

$$i_{abc} = i_s^+ \cos(\omega t - k\frac{2\pi}{3}) + i_s^- \cos(-\omega t - k\frac{2\pi}{3}) \tag{1}$$

where superscripts + and - define the coefficients for the positive, negative sequence components, and $k = 0, 1, 2$. Using the Clarke transformation [23], the current vector in the $\alpha\beta$ plane is given by Equation (2):

$$i_{s\alpha\beta} = i_s^+ \begin{bmatrix} \cos(\omega t) \\ \sin(\omega t) \end{bmatrix} + i_s^- \begin{bmatrix} \cos(-\omega t) \\ \sin(-\omega t) \end{bmatrix} \tag{2}$$

The $\alpha\beta$ to d-q frame transformation can be obtained by multiplying $i_{s\alpha\beta}$ by Equation (3). After that, the positive and negative sequence components in the d-q axis are as follow:

$$T_{d-q} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \tag{3}$$

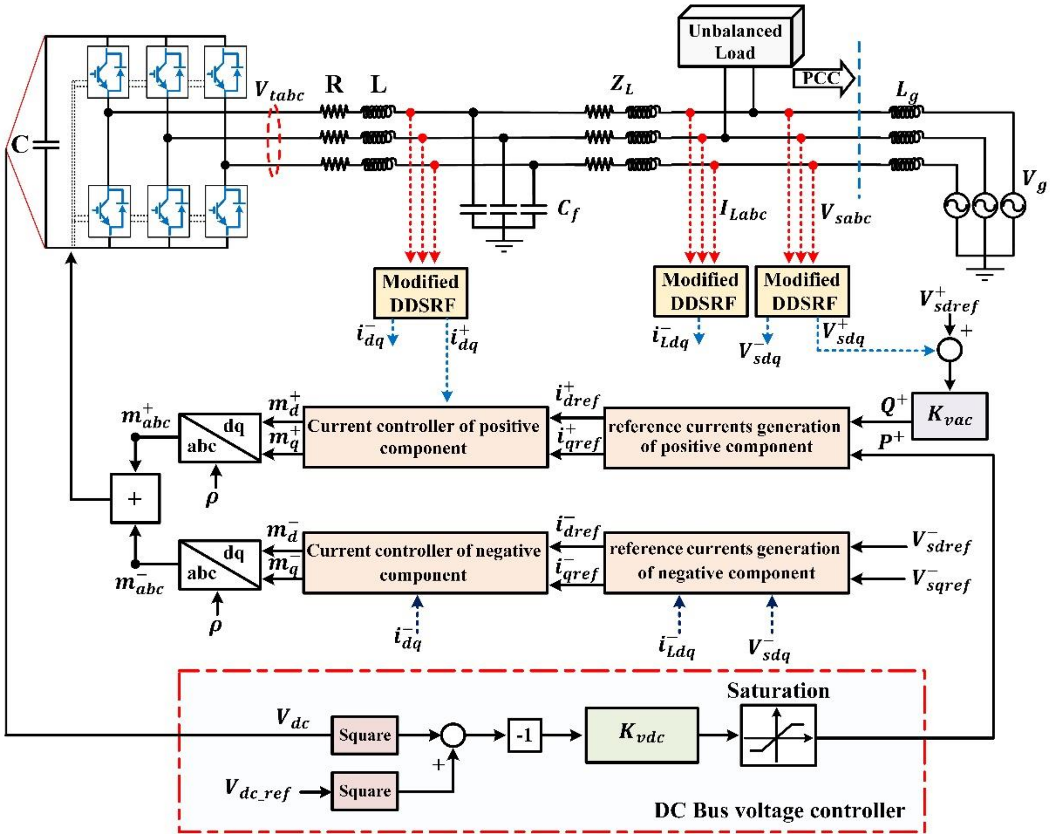


Figure 1. Schematic diagram of STATCOM under unbalance condition

$$i_{dq}^{+} = \underbrace{i_{dq}^{+}}_{DC\ term} + \underbrace{[\cos(\theta^{+}-\theta^{-}) - j\sin(\theta^{+}-\theta^{-})]i_{dq}^{-}}_{Oscillation\ term} \tag{4}$$

$$i_{dq}^{-} = \underbrace{i_{dq}^{-}}_{DC\ term} + \underbrace{[\cos(\theta^{-}-\theta^{+}) - j\sin(\theta^{-}-\theta^{+})]i_{dq}^{+}}_{Oscillation\ term} \tag{5}$$

where

$$\begin{aligned} i_d^{+} &= I^{+}\cos\left(\delta^{+}-\varphi^{+}\right) \\ i_q^{+} &= I^{+}\sin\left(\delta^{+}-\varphi^{+}\right) \\ i_d^{-} &= I^{-}\cos\left(\delta^{-}-\varphi^{-}\right) \\ i_q^{-} &= I^{-}\sin\left(\delta^{-}-\varphi^{-}\right) \end{aligned} \tag{6}$$

$$\begin{aligned} \theta^{+} &= \omega t + \varphi^{+} \\ \theta^{-} &= -\omega t + \varphi^{-} \end{aligned} \tag{7}$$

In the above equation, φ^{+} and φ^{-} are initial phases of positive and negative sequence of voltage, respectively. Also, δ^{+} and δ^{-} are initial phases of positive and negative sequence components.

Through Equations (4) and (5), it is clear that the components of the positive and negative sequence offer an oscillatory term and a DC term. DSRF current controllers function under unbalanced perturbations is not perfect because it cannot eliminate current and voltage oscillatory terms. To solve this problem, Decouple Double Synchronous Reference Frame (DDSRF) can be used [21] with a schematic diagram as shown in Figure 2. This method to remove oscillatory term is advantageous and stated as below:

$$\begin{aligned} i_{dq}^{+} = {} & \underbrace{i_{dq}^{+}}_{DC\ term} + \underbrace{[\cos(\theta^{+}-\theta^{-}) - j\sin(\theta^{+}-\theta^{-})]i_{dq}^{-}}_{Oscillation\ term} - \\ & \underbrace{[\cos(\theta^{+}-\theta^{-}) - j\sin(\theta^{+}-\theta^{-})].(\underbrace{i_{dq-ref}^{-} - \Delta i_{dq}^{-}}_{Dc\ term})}_{Cross-Coupling\ term} \end{aligned} \tag{8}$$

$$\begin{aligned} i_{dq}^{-} = {} & \underbrace{i_{dq}^{-}}_{DC\ term} + \underbrace{[\cos(\theta^{-}-\theta^{+}) - j\sin(\theta^{-}-\theta^{+})]i_{dq}^{+}}_{Oscillation\ term} - \\ & \underbrace{[\cos(\theta^{-}-\theta^{+}) - j\sin(\theta^{-}-\theta^{+})].(\underbrace{i_{dq-ref}^{+} - \Delta i_{dq}^{+}}_{Dc\ term})}_{Cross-Coupling\ term} \end{aligned} \tag{9}$$

In the above equations, and of course, according to Figure 2, the reference currents are assumed to be fully DC and non-oscillating. Given that, under unbalanced conditions, reference currents have oscillating components, the estimation of oscillatory components using reference currents is not as efficient as required. Therefore, according to Figure 3, in this paper the modified DDSRF, based on the measured currents is used to estimate oscillatory components:

$$i_{dq}^{+} = \underbrace{i_{dq}^{+}}_{DC\ term} + \underbrace{[\cos(\theta^{+}-\theta^{-}) - j\sin(\theta^{+}-\theta^{-})]i_{dq}^{-}}_{Oscillation\ term} - \underbrace{[\cos(\theta^{+}-\theta^{-}) - j\sin(\theta^{+}-\theta^{-})].i_{dq}^{-\prime}}_{Cross-Coupling\ term} \tag{10}$$

$$i_{dq}^{-} = \underbrace{i_{dq}^{-}}_{DC\ term} + \underbrace{[\cos(\theta^{-}-\theta^{+}) - j\sin(\theta^{-}-\theta^{+})]i_{dq}^{+}}_{Oscillation\ term} - \underbrace{[\cos(\theta^{-}-\theta^{+}) - j\sin(\theta^{-}-\theta^{+})].i_{dq}^{+\prime}}_{Cross-Coupling\ term} \tag{11}$$

where

$$i_{dq}^{+\prime} = i_{dq}^{+} \times \frac{S^{2}+\omega_n^{2}}{S^{2}+2\xi\omega_n+\omega_n^{2}}$$

$$i_{dq}^{-\prime} = i_{dq}^{-} \times \frac{S^{2}+\omega_n^{2}}{S^{2}+2\xi\omega_n+\omega_n^{2}}$$

In above equations, $\frac{S^{2}+\omega_n^{2}}{S^{2}+2\xi\omega_n+\omega_n^{2}}$ is transfer function of notch filter. ξ and ω_n are damping ratio and cut-off frequency.

3. 2. Reference Currents Generation of Positive and Negative Sequence Components

3. 2. 1. Reference Currents Generation of Positive Sequence Component

After separating the positive and negative components, it is important to calculate active and reactive power delivered to the AC system based on the theory of instantaneous power.

Accordingly, active and reactive power in the d-q frame are as follow [24]:

$$P_S^{+}(t) = \frac{3}{2}\left[V_{sd}^{+}(t)i_d^{+}(t) + V_{sq}^{+}(t)i_q^{+}(t)\right] \tag{12}$$

$$Q_S^{+}(t) = \frac{3}{2}\left[-V_{sd}^{+}(t)i_q^{+}(t) + V_{sq}^{+}(t)i_d^{+}(t)\right] \tag{13}$$

As an assumption, if the PLL is in a steady state, $V_{sq}^{+} \approx 0$. Considering this, the influence between V_{sd}^{+} and V_{sq}^{+} is eliminated. Therefore, Equations (12) and (13) can be written as:

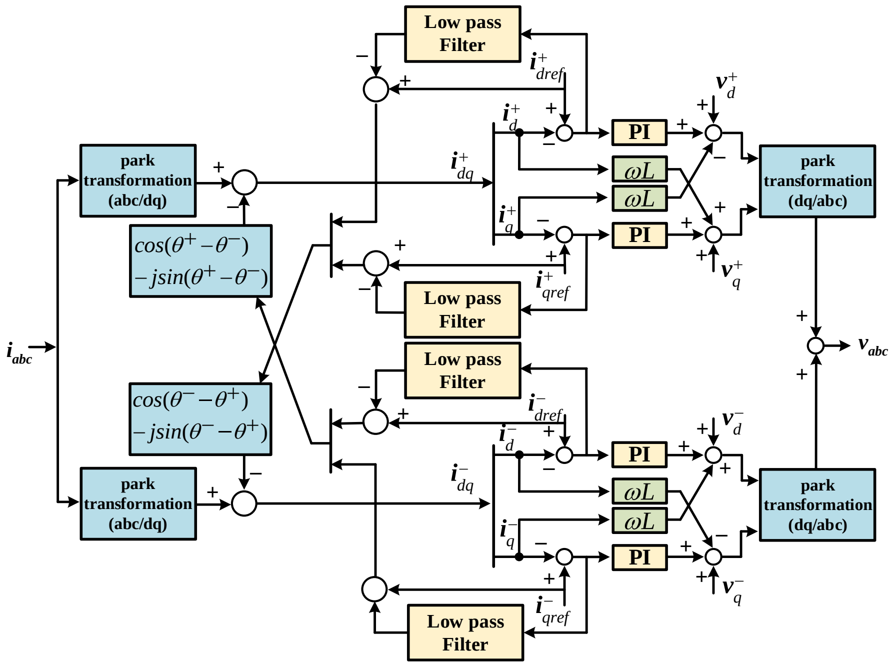


Figure 2. Presented DDSRF in reference [21]

$$P_S^+(t) = \frac{3}{2}\left[V_{sd}^+(t)\, i_d^+(t)\right] \tag{14}$$

$$Q_S^+(t) = \frac{3}{2}\left[-V_{sd}^+(t)\, i_q^+(t)\right] \tag{15}$$

Based on above equations P_S^+ and Q_S^+ can be controlled by i_d^+ and i_q^+ respectively; thus:

$$i_{dref}^+(t) = \frac{2}{3V_{sd}^+} P_S^+(t) \tag{16}$$

$$i_{qref}^+(t) = \frac{-2}{3V_{sd}^+} Q_S^+(t) \tag{17}$$

3. 2. 1. Reference Currents Generation of Negative Sequence Component

The PCC open-loop control pattern can be realized using KCL on the STATCOM output capacity filter. Figure 1 shows that after converting these equations into the d-q frame, the following equations for negative sequential components are reached:

$$C_f \frac{dV_{sd}^-(t)}{dt} = I_d^-(t) - I_{Ld}^-(t) - C_f\,\omega(t)\,V_{sq}^-(t) \tag{18}$$

$$C_f \frac{dV_{sq}^-(t)}{dt} = I_q^-(t) - I_{Lq}^-(t) + C_f\,\omega(t)\,V_{sd}^-(t) \tag{19}$$

where $\omega(t) = \frac{d\rho}{dt}$ which ρ represent a phase shift in the PLL.

As it can be seen in Equations (18) and (19), there is a couple between V_{sd}^- and V_{sq}^- that this couple eliminated by feed-forward compensator (Figure 4). For the purpose of designing the $k_{d,qv}^-$ controllers, the simplified block diagram of the negative sequence components closed-loop voltage control is regarded in Figure 4. Here, τ_i is the desired time constant of the closed-loop control system, explained in the next part. The transfer function of the open-loop voltage control system has a pole leading to the coordinate; taking into account this, the steady-state error of the closed-loop system is zero, so that the $k_{d,qv}^-$ can be considered as a proportional controller with the k_{pv} value.

3. 3. Current Controllers of Positive and Negative Sequence Components

The control model loop of STATCOM can be extended by applying KVL on the output inductance filter. From Figure 1, having transformed these equations into d-q frames:

$$L\frac{dI_d^+(t)}{dt} + (R + r_{on})\, I_d^+(t) = V_{td}^+(t) - V_{sd}^+(t) + L\omega_0 I_q^+(t) \tag{20}$$

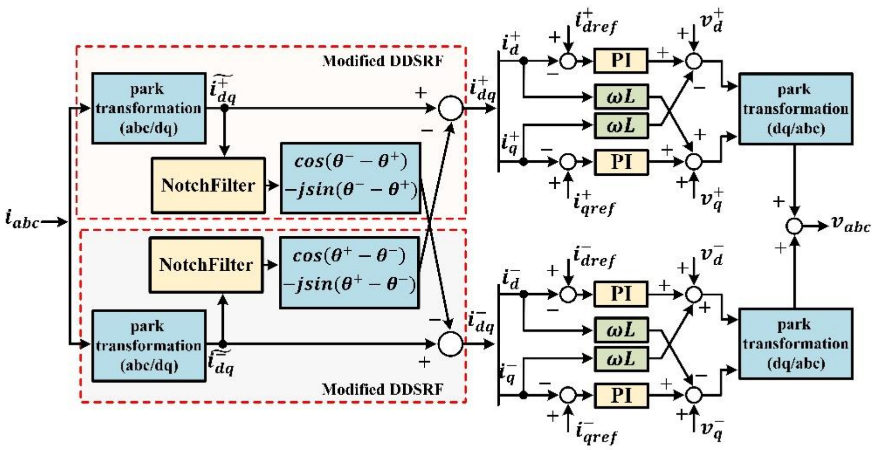


Figure 3. Modified DDSRF

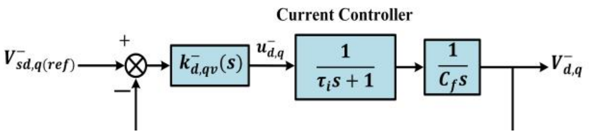


Figure 4. Simplified block diagram of the negative voltage control loop

$$L\frac{dI_q^+(t)}{dt}+(R+r_{on})I_q^+(t) =V_{tq}^+(t)-V_{sq}^+(t)-L\omega_0 I_d^+(t) \tag{21}$$

$$L\frac{dI_d^-(t)}{dt}+(R+r_{on})I_d^-(t) =V_{td}^-(t)-V_{sd}^-(t)-L\omega_0 I_q^-(t) \tag{22}$$

$$L\frac{dI_q^-(t)}{dt}+(R+r_{on})I_q^-(t) =V_{tq}^-(t)-V_{sq}^-(t)+L\omega_0 I_d^-(t) \tag{23}$$

According to principles of operation, the AC side terminal voltage of converter using in STATCOM deduced from the following equations [25]:

$$V_{td}^{\pm}(t)=\frac{V_{dc}}{2}m_d^{\pm} \qquad \& \qquad V_{tq}^{\pm}(t)=\frac{V_{dc}}{2}m_q^{\pm}$$

Due to the $L\omega_0$ term's presence in the above equations, there is a couple between I_d^+ and I_q^+ in both positive and negative sequence components. To decouple the dynamics, by using $u_{dq}(t)=V_{tdq}(t)-V_{sdq}(t)\pm L\omega_0 I_{dq}(t)$ in Equations (20)-(23) and rewriting equations in the Laplace domain:

$$LsI_{d,q}^{\pm}(s)=-(R+r_{on})I_{d,q}^{\pm}(s)+u_{d,q}^{\pm} \rightarrow I_{d,q}^{\pm}=\frac{u_d^+}{Ls+(R+r_{on})} \tag{24}$$

r_{on} is the converter internal resistance, and $u_{d,q}^{\pm}$ is the control command that defines in the before paragraph; other variables are defined in the NOMENCLATURE table. For the $k_{d,qI}^{\pm}$ control design, the closed-loop model of the current positive and negative components is considered functional schematics in Figure 5 and described by Equations (20)-(23). In order to equalize the steady-state error to zero, $k_{d,qI}^{\pm}$ is considered as a proportional-integral (PI) controller:

$$k_{d,qI}^{\pm}=k_p+\frac{k_i}{s} \tag{25}$$

Here k_p and k_i are the proportional and integral coefficients of the PI current controller. Thus, according to Figure 5, the transfer function of the open-loop system can be written in the following way:

$$T_{ol}(s)=\left(\frac{k_p}{Ls}\right)\left(\frac{s+\frac{k_i}{k_p}}{s+\frac{R+r_{on}}{L}}\right) \tag{26}$$

Taking into account Equation (26), the transfer function of the open-loop system has a steady pole at $p=-\frac{R+r_{on}}{L}$ Of course, this pole is partly close to the origin and is consistent with a slow response from the system. To ameliorate the system frequency response, the pole can be neutralized by the PI controller zero. For the closed-loop transfer function of the system:

$$G_i(s)=\frac{i_{d,q}^{\pm}(s)}{i_{d,q\,ref}^{\pm}(s)}=\frac{1}{\tau_i s+1} \tag{27}$$

Equation (27) is a first-order transfer function. τ_i is the desired time constant of the closed-loop control system, which should be very small to have a fast frequency response in the controller. On the other side by growing $\frac{1}{\tau_i}$, the closed-loop control system's bandwidth will rise considerably.

3. 4. DC Bus Voltage Controller The main purpose of control for the controlled DC voltage supply port is to adjust the DC bus voltage V_{dc} a feedback compensator with a required reference control. In the STATCOM system of Figure 1, the power is formulated as [25]:

$$P_{ext}-P_{loss}-\frac{d}{dt}\left(\frac{1}{2}CV_{dc}^2\right)=P_{dc} \tag{28}$$

where V_{dc}^2 is the output, P_{dc} is the control input, and P_{loss}, P_{ext} are the disturbance inputs. Equation (25) in the Laplace domain provides the voltage dynamics of the DC bus [25]:

$$G_v(s)=\frac{V_{dc}^2}{P_S}=-\left(\frac{2}{C}\right)\frac{\tau S+1}{S} \tag{29}$$

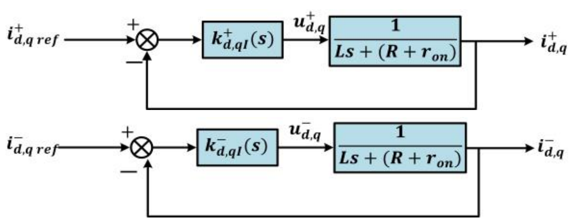


Figure 5. Simplified block diagram of the current control loop

In which the time constant τ is

$$\tau = \frac{2LP_{ext}}{3V_{sd}^2} \tag{30}$$

As shown in Figure 1 V_{dc}^2 is compared with $V_{dc\_ref}^2$; the error signal is processed by the compensator K_{vdc} , and P^+ is produced. The current controller regulates P^+ at P_{ref}^+ ; therefore, we can write:

$$G_i(s) = \frac{P^+(s)}{P_{ref}^+(s)} = \frac{1}{\tau_i s + 1}$$

Figure 6 shows a DC bus voltage regulator block diagram for the STATCOM in Figure 1. The closed-loop system is composed of the compensator $K_{vdc}(s)$, current controller $G_i(s)$, and control plant $G_v(s)$ .Thus, the open-loop transfer function is

$$\ell(s) = -K_{vdc}(s)G_i(s)G_v(s) \tag{31}$$

If consider $K_{vdc}(s) = \left(\frac{C}{2}\right)\frac{H(s)}{S}$ in (31) we found

$$\ell(s) = G_i(s)H(s)\frac{\tau S + 1}{S^2} \tag{32}$$

To ensure that the phase delay due to $G_i(s)$ is negligible, $G_i(s) = 1$.

Based on defining the frequency response, the magnitude of the loop gain is infinity to the control signal frequency. To follow a control approach with zero stationary status errors, the unstable poles of the Laplace transform must be incorporated into the compensator. Likewise:

$$H(s) = h\frac{S+\alpha}{S+\beta}$$

Consequently

$$K_{vdc}(s) = h\frac{S+\alpha}{S(S+\beta)} \tag{33}$$

where h, and α , and β are coefficients of lead controller.

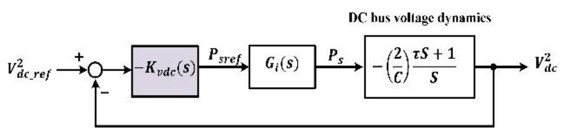


Figure 6. block diagram of DC-bus voltage regulation

4. RESULTS AND DISCUSSION

In this section, to confirm the proposed control system efficiency, the schematics presented in Figure 1 is simulated using MATLAB/SIMULINK. Here, to prove the introduction statements, a control technique based on DDSRF [21] is simulated and compared with the proposed method. The simulation details are listed in Tables 1 and 2.

4. 1. Comparison of Conventional DDSRF and Modified DDSRF

As mentioned in previous sections, when reference currents are completely DC and do not have an AC sequence component, in order to decouple the sequence currents from each other, the conventional DDSRF [21] is accountable. However, when the reference currents are not DC and have an AC component, the conventional DDSRF cannot be held accountable. To demonstrate this pretension, a simulation is carried out in the condition that the reference current

TABLE 1. Parameters of simulated system

Parameter	Value
Nominal power of inverter [kW]	20
Phase voltage [v]	391 (peak)
Dc link capacitor [µF]	9812
Angular frequency [rad/sec]	377
Switching frequency [kHz]	3
Unbalance load [Ω]	0.01+j0.2
Inverter filter inductance [µH]	100
Inverter filter capacitance [µF]	2500
Distribution line [Ω]	0.01+j3.7
damping coefficient of notch filter	$\xi = 0.707$
natural frequency of notch filter	$F_n = 120$Hz

TABLE 2. Controller's characterization

Parameter	Value
$k_{dv}^- = k_{qv}^-$	1.6 $[\Omega^{-1}]$
$k_{dI}^+ = k_{qI}^+ = k_{dI}^- = k_{qI}^-$	$0.2 + 4.14/S$ [Ω]
K_{vdc}	$1868\frac{S+19}{S(S+2077)}$ $[\Omega^{-1}]$
K_{vac}	$\frac{2}{S}$ [MA]

of the q axis at the time t=1s is changed $i^{+}_{q\_ref} = 4 + \sin(120\pi t)$, and the reference current of the d axis at the time t=1.1s is changed to $i^{-}_{d\_ref} = 4$. Then, at t=1.2s, a sinusoidal term in form $i^{-}_{d\_ref} = \sin(120\pi t)$ is added. The results of comparison between the DDSRF and modified DDSRF are in Figures 7 and 8. As shown in Figures 7 and 8, when the reference current is not DC and has an AC component, the conventional DDSRF cannot appropriately extract the DC component. In contrast, the proposed DDSRF can correctly eliminate the ac component and extract the DC component.

4. 2. Voltage Balancing, DC Bus Voltage Control and Regulation Voltage in STATCOM with Proposed Method The results are extended to the modified DDSRF after ensuring that the conventional DDSRF cannot operate appropriately in a harmonic condition. A typical STATCOM can be used to control DC-link voltage, and of course, it can be utilized in order to regulate PCC voltage. In this paper, in addition to implementing these objectives, the voltage unbalance compensation at the PCC is performed using the modified DDSRF structure. The simulation time is organized as follows:

1. At t=0.3s, the reference of DC link voltage is changed from 1500v to 1700v.

2. At t=0.4s unbalanced load is added.

3. At t=1.9s, the reference of three-phase voltage is changed from 391v to 420v.

The unbalance load causes a voltage unbalance at the PCC. Figure 9 illustrates the PCC voltage when the proposed control system is employed for compensating the unbalanced voltage. This figure shows that the proposed control strategy effectively compensates for the unbalanced voltage.

Figure 10 presents the results of the FFT analysis of the PCC voltage. As can be observed in Figure 10a, when the conventional DDSRF method is used, the total harmonic distortion (THD) is 35.95%, which is bigger than the standard limit of 5% for distribution networks.

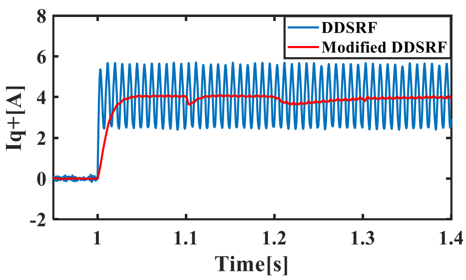


Figure 7. Positive sequence q component of the current under oscillation condition

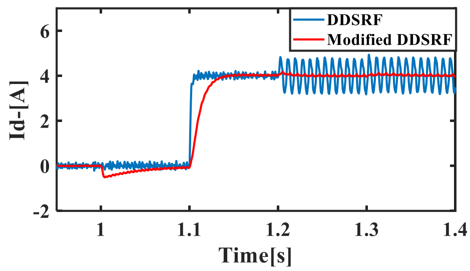


Figure 8. Negative sequence d component of the current under oscillation condition

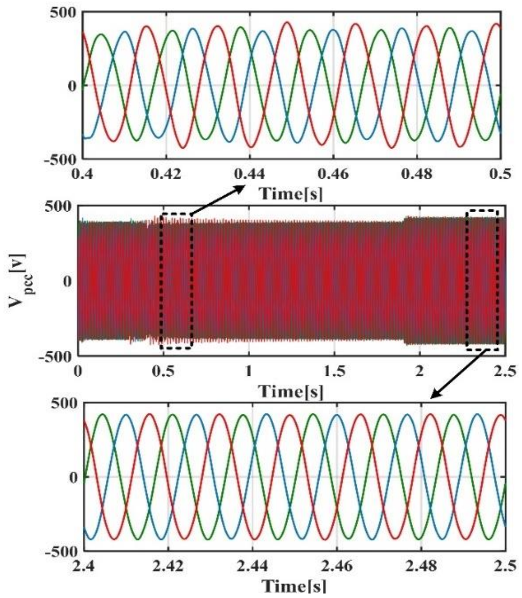
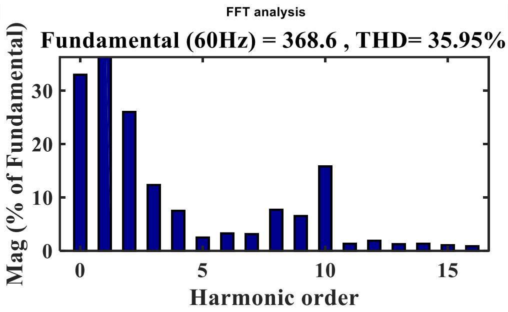


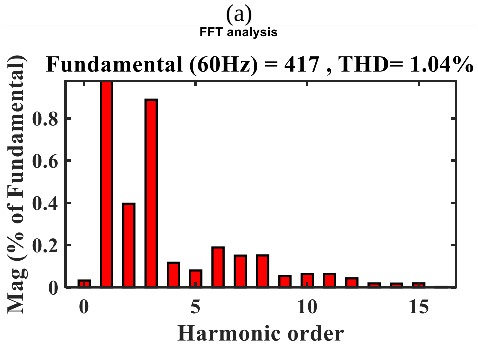
Figure 9. compensation of PCC voltage of STATCOM using modified DDSRF

The increase of the THD, in this case, is due to that the conventional DDSRF cannot effectively degrade the oscillatory coupling between the positive and negative sequence components, which leads to system instability. Using the modified DDSRF-based control method, the THD indicates that the results of FFT analysis is 1.04% within its standard limit (Figure 10b).

Figure 11 shows the voltage unbalance factor (VUF). According to the IEC description, the VUF is defined as the ratio of negative sequence voltage to the positive sequence voltage ($VUF\% = \frac{|V_{-}|}{|V_{+}|} \times 100$) [26]. This factor must be limited to under 2%. Figure 11a demonstrates that for the proposed method, after about 1.1 seconds, the VUF is reduced to less than 2%. Figure 11b shows that the control method based on conventional DDSRF causes instability. That is why suggesting the other forms of this method is avoided.



(a)



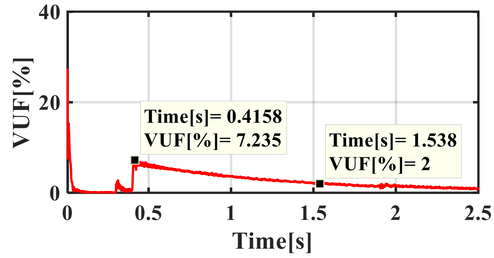
(b)

Figure 10. FFT analysis a) Modified DDSRF b) conventional DDSRF

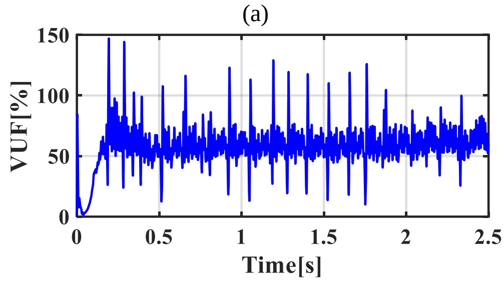
Figures 12 and. 13 illustrate the positive and negative sequences of voltage in the d-q frame prominently. As can be seen, the positive sequence voltage in the d axis tracks its reference (391-420 V), and the positive component in the q axis and the negative components in the *d-q* axis are track zero, which proves the proper performance of the inverter control system. Furthermore, it is crystal clear that the amplitude of voltage in the negative sequence in the d and q axis decreases efficaciously. As a result, the value of the THD and the VUF remain acceptable at the steady-state.

Figure 14 shows the output active and reactive power of the STATCOM. This figure explains that, since the STATCOM is the device for controlling the reactive power and voltage control, the active power injecting it would be zero. As shown in Figure 14, at t=0.4s, when an unbalanced load is added to the system, the STATCOM control system delivers approximately 8×10^{5} VAR of the reactive power to compensate for the unbalanced voltage. Also, at t=1.9s, when the AC voltage reference varies from 391v to 420v, STATCOM injected approximately 1.2×10^{6} VAR of the reactive power to regulate of PCC voltage. It is noticeable that DDSRF based method has an accurate performance and provides a fast-dynamic response.

Figure 15 illustrates the controlled DC-voltage port time response when a feed-forward compensator is utilized in the DC-bus voltage control loop. At t=0.3s

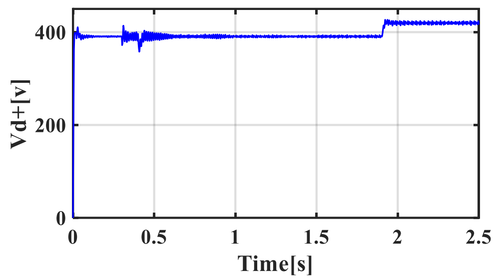


(a)

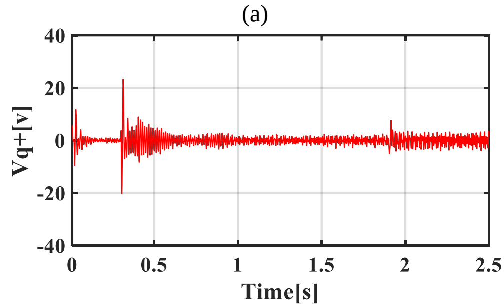


(b)

Figure 11. Voltage Unbalance Factor a) Modified DDSRF b) conventional DDSRF

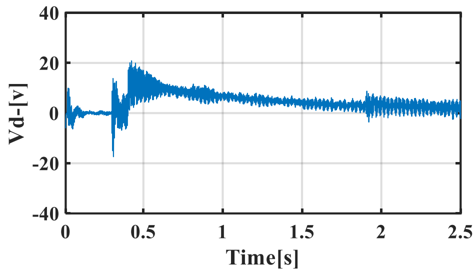


(a)

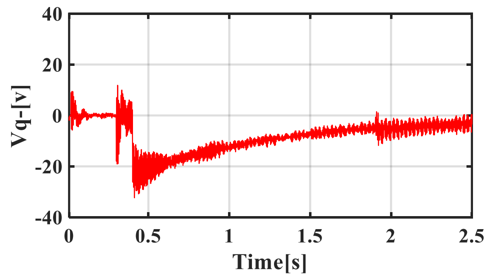


(b)

Figure12. Positive components of voltage at PCC for: a) d axis, b) q axis



(a)



(b)

Figure 13. Negative components of voltage at PCC for: a) d axis, b) q axis

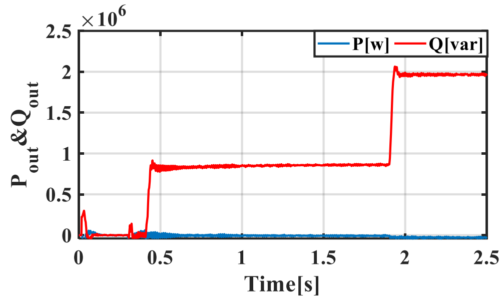


Figure14. Injected active and reactive power by STATCOM

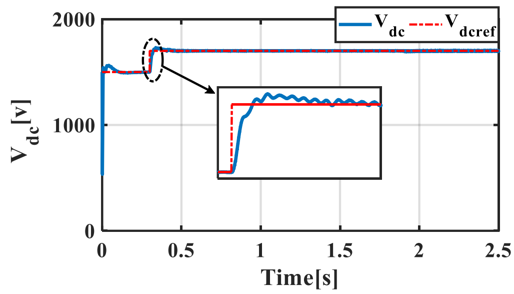


Figure 15. DC-link voltage control

reference of DC link voltage is changed stepwise from 1500v to 1700v. Consequently, to move V_{dc} up, K_{vdc} commands a negative P_{ref}^{+} to import real power from the AC system to the STATCOM DC side; P_{ref}^{+} is saturated to its negative limit for a brief period. It is perceptible that V_{dc} is regulated at $V_{dc\_ref} = 1700\,\text{v}$, and P_{ref}^{+} assumes small values corresponding to the VSC power loss.

5. CONCLUSION

This paper investigates a scheme for STATCOM control under unbalanced voltage to reduce oscillating coupled between the positive and negative sequence components using modified DDSRF. Simulation results show that the oscillating couple emerging in positive and negative sequence components of *d* and *q* frame in the conventional DDSRF is eliminated using the proposed DDSRF method and the system performance under unbalance voltage condition is improved. Applying the proposed technique, the magnitude of voltage unbalance factor and total harmonic distortion for voltage at PCC is acceptable. In addition, injected reactive power by means of STATCOM depends on PCC voltage variations. Also, regulation of AC voltage and control of DC-link voltage by employing feed-forward compensator are adequately performed to ensure the STATCOM proper functioning.

6. LIMITATION AND FUTURE WORK

The limitations of the proposed control strategy as well as the issue that need to be considered in order to extend the proposed approach are summarized as follows:
1) It is assumed that there is no load connected to DG's terminal. So, the unbalanced voltage at the DG's terminal does not negatively impact the loads.
2) It is assumed that the inverter has sufficient capacity for unbalanced voltage compensation.

As future work, a harmonic load can be added to the STATCOM and the DDSRF relations, and of course, voltage balancing and DC-link power port control can be expanded to the harmonic conditions. In this paper, only the second harmonic, 2W, is eliminated by the DDSRF, and the other harmonics must be developed and studied.

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Persian Abstract

چکیده

بسیاری از منابع و بارهای تکفاز سبب بروز نامتعادلی در ریزشبکه می‌شوند. نامتعادلی ولتاژ کیفیت توان ریزشبکه را کاهش می‌دهد و از تبعات آن عملکرد نادرست و قطعی بارها و تجهیزات مصرف‌کنندگان ریزشبکه است. همچنین ولتاژ نامتعادل اثرات مخربی بر موتورهای القایی، مبدل‌های الکترونیک قدرت و درایوهای تنظیم سرعت دارد. جبران‌ساز استاتیک سنکرون به عنوان یک بخش مؤثر از ادوات FACTS (سیستم انتقال جریان متناوب انعطاف‌پذیر) به طور گسترده‌ای به عنوان یک جبران‌ساز موازی در کنترل توان راکتیو و تنظیم ولتاژ در شبکه‌های توزیع کاربرد دارد. تحت شرایط نامتعادل یک کوپل نوسانی بین مولفه‌های توالی مثبت و منفی در محور d-q به وجود می‌آید. این مقاله یک کنترل کننده ولتاژ PCC (نقطه اتصال مشترک) را در قاب مرجع سنکرون دوگانه مجزا (DDSRF) را ارایه می‌دهد که نامتعادلی ولتاژ PCC را جبران می‌کند و همچنین کوپل نوسانی نیز توسط STATCOM (جبران‌ساز سنکرون استاتیک) با استفاده از حلقه‌های مجزای مثبت و منفی برطرف می‌شود. پیاده‌سازی سیستم DDSRF پیشنهاد شده شامل چندین مرحله است: ابتدا سیگنال‌های نامتعادل به منظور جداسازی مولفه‌های مثبت بر خلاف جهت عقربه‌های ساعت چرخانده می‌شوند بار دیگر همان سینگال‌ها به منظور جدا شدن مولفه‌های منفی در جهت عقربه‌های ساعت چرخانده شده و در پایان با استفاده از روابط ریاضی سیستم کنترل پیشنهادی DDSRF معرفی می‌گردد که این سیستم قادر است مولفه‌های مثبت و منفی را به طور جداگانه کنترل کند. در این مقاله علاوه بر کنترل ولتاژ خازن DC تنظیم ولتاژ PCC نیز انجام شده است. طرح سیستم کنترل پیشنهادی تحت شرایط نامتعادل طراحی شده است و نتایج شبیه‌سازی کارایی و اثربخشی استراتژی کنترلی پیشنهادی را تضمین می‌کند.