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A Moving Average Filter based DSTATCOM Control Approach

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Abstract: Self-excited induction generators (SEIGs) are commonly preferred in stand-alone renewable energy systems due to their low cost and robust construction. However, the voltage and frequency stability at the SEIG output may be adversely affected by varying reactive and active power demands depending on the load profile. In such systems, DSTATCOM is used to provide voltage and frequency regulation, and its performance largely depends on the applied control algorithm. In this study, a moving average filter (MAF) based *dq* control algorithm is proposed for DSTATCOM supported SEIG systems. The MAF structure contributes to more accurate calculation of reference source currents by reducing the effect of harmonic content. The proposed control method is tested under nonlinear load and unbalanced-nonlinear load conditions. The results show that the system maintains voltage and frequency stability and successfully suppresses disturbances.

Keywords Distribution Static Compensator (DSTATCOM), Moving Average Filter (MAF), Self-Excited Induction Generator (SEIG), Wind Energy.

1. Introduction

The importance of renewable energy sources is increasing in accordance with the increasing global energy demand and environmental sustainability targets. Among these sources, wind energy stands out with its clean, inexhaustible, and low operating cost structure and is considered as a strategic alternative (Kundu et al. 2024). The generator technology used in wind turbines plays a direct determining role in the efficiency, reliability and power quality of the system.

Self-Excited Induction Generators (SEIGs) stand out with their low cost, robust construction, brushless rotor systems and low maintenance requirements, especially in small-scale off-grid applications (Sibrahim et al. 2024). In addition, standard asynchronous machines can be used as generators with a simple capacitor bank, making SEIG systems an economical and accessible solution. In this respect, they are widely preferred in rural areas, mobile energy systems and microgrids based on variable energy sources such as wind. However, SEIGs have a sensitive structure against load changes. This is because the output voltage and frequency of the generator can only remain at reference values if the active power balance as well as the reactive power demanded by the load and the SEIG is correctly balanced. As the load profile changes, the active power demand changes as well as the reactive power demand, which may cause voltage fluctuations and rotor speed deviations in the SEIG system and adversely affect the frequency stability. Therefore, the regulation of SEIG output in terms of both voltage and frequency requires the system to have a control infrastructure that can react flexibly and quickly to dynamic conditions (Shailly et al. 2025)

To meet this requirement, passive compensation methods such as fixed capacitor banks were first used to provide the reactive power demanded by the SEIG and the load, and then solutions such as thyristor-controlled Static Var Compensator (SVC) were developed. Although these systems offer attractive options due to their low cost and applicability, they are insufficient to meet the dynamic needs of the systems due to their limited response speed to sudden load changes, their inability to suppress harmonic distortions and their low sensitivity in voltage regulation. In addition, these methods can only provide reactive power compensation; since they cannot provide active power support, they cannot contribute to frequency regulation in SEIG systems. Especially under harmonic and unbalanced load conditions, these limitations become more apparent and have negative effects on system stability, power quality and reliability. To overcome these disadvantages, active power electronics-based solutions, especially Distribution Static Compensator (DSTATCOM) topologies come to the fore (Giri et al. 2020). DSTATCOM offers an effective solution for SEIG systems thanks to its ability to react quickly to sudden changes in load and to perform both reactive power compensation and harmonic suppression functions simultaneously. DSTATCOM, which can dynamically adapt to different load scenarios thanks to its power electronics-based structure, ensures that the system voltage remains at the reference value, while also improving power quality (Ozer et al. 2024). On the other hand, for the SEIG output frequency to remain stable, the active power drawn from the generator must be kept in balance. Sudden changes in the load may disturb this balance and cause fluctuations in the rotor speed and thus frequency deviations. To stabilize this situation, an battery energy storage system (BESS) is integrated into the DSTATCOM structure to provide not only reactive but also active power support. Thus, a part of the active power requirement of the system is met through DSTATCOM, relieving the load on the SEIG and keeping the frequency constant.

The effectiveness of DSTATCOM directly depends on the performance of the control algorithm. In this context, there are various control methods developed in literature. Methods such as Instantaneous Reactive Power Theory (IRPT), Synchronous Reference Frame (*dq*) and Current Synchronous Detection (CSD) are widely used to calculate the reference currents required for the control of DSTATCOM (Ram et al. 2024). Among these methods, the *dq* method stands out due to its time-invariant (DC level) components, high immunity to harmonics and ease of application (Rajendran et al. 2013).

Low Pass Filters (LPFs) are generally used during the separation of load current components in SRF structure. However, these filters may cause performance losses in harmonic and unbalanced load conditions. While LPFs cause phase delay and accuracy loss in transient states, they are insufficient especially in suppressing low frequency harmonics. In addition, asymmetric behavior between phases under unbalanced load conditions adversely affects the stability of classical filtering structures.

In this study, the advantages of the *dq*-based structure are retained; however, a control algorithm is proposed by integrating a moving average filter (MAF) instead of classical LPF modules. MAF provides a more stable filtering in transient states by averaging the signal over the time window. MAF, which is more effective than LPF in suppressing sudden fluctuations especially in signals containing harmonics, produces accurate reference current components by better tolerating under unbalanced load conditions. Thus, DSTATCOM can intervene in the SEIG system faster and more accurately, significantly increasing system performance in terms of voltage regulation, SEIG frequency and power quality.

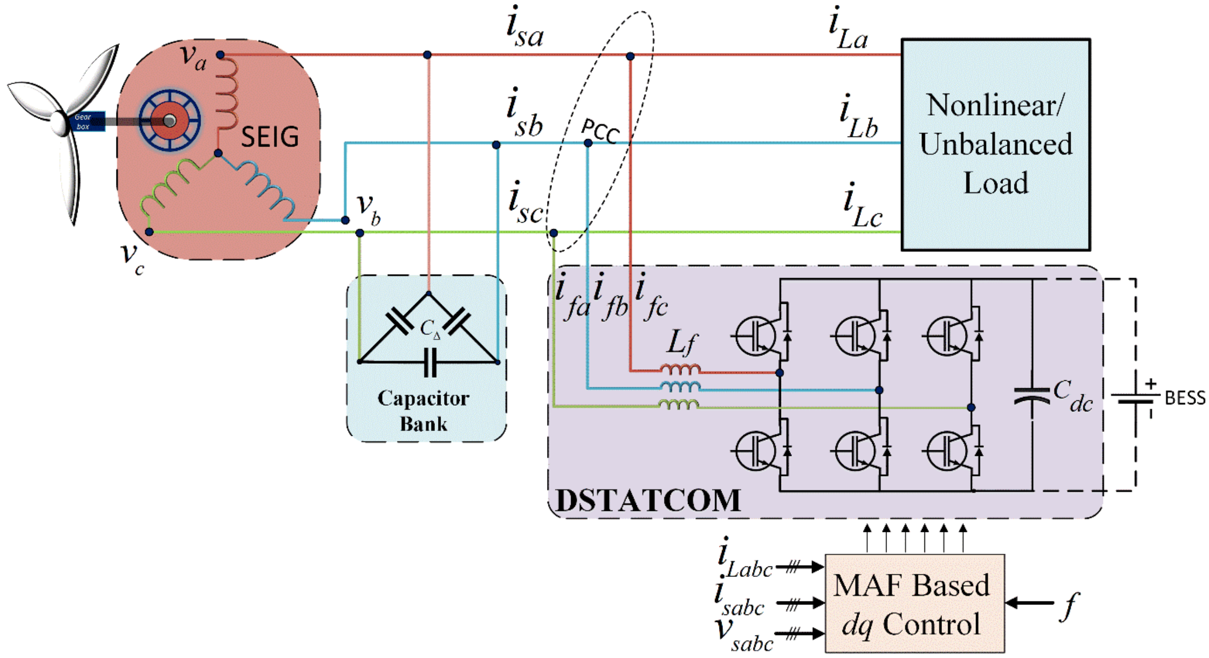

Figure 1 Schematic of DSTATCOM-based SEIG system

2. DSTATCOM-based SEIG System

Figure 1 shows the general structure of the DSTATCOM supported SEIG system. The system consists of a self-excited induction generator (SEIG), delta-connected excitation capacitors, nonlinear/unbalanced loads, and DSTATCOM-assisted energy storage system (BESS) providing active and reactive power. The reactive power required for the magnetization of the SEIG is provided by the capacitor banks; these capacitors are also involved in the suppression of harmonic components caused by the high switching frequency of the voltage source converter (VSC) (Chilipi et al. 2020).

DSTATCOM is connected in parallel with the point of common coupling (PCC) of the system via three-phase coupling inductances (L_f). DSTATCOM supports voltage regulation by activating to meet the reactive power requirements of both SEIG and the load in case of load changes. It also contributes to frequency regulation by providing active power through the integrated BESS structure and keeps the active load on the SEIG constant.

VSC, which is the main component of DSTATCOM, consists of insulated gated bipolar transistors (IGBTs) and generates three-phase output voltage through PWM control signals.

3. MAF-based *dq* control method

Figure 2 presents the block diagram of the proposed MAF-based *dq* control method. In this structure, the load currents are subjected to abc-*dq* conversion and the fundamental components of the obtained i_{Ld} and i_{Lq} are obtained using a moving average filter (MAF). Thus, the harmonic content is filtered, and a more stable structure is created for reference current calculations. The obtained active and reactive current components are processed by PI controllers; thus, reference source currents i_{sa}^* i_{sb}^* and i_{sc}^* are generated and VSC is controlled based on these currents.

3.1 Description of the suggested MAF

The LPFs used to filter i_{Ld} and i_{Lq} suffer from two problems: they lead to the phase delay and cannot sufficiently suppress harmonic components caused by nonlinear and unbalanced loads. To address these challenges, in this paper, moving average filters (MAFs) are utilized instead of LPFs, as can be seen in Figure 2. The MAF structure is uncomplicated and straightforward to implement, which has contributed to its growing popularity in recent times (Ozer et al. 2022).

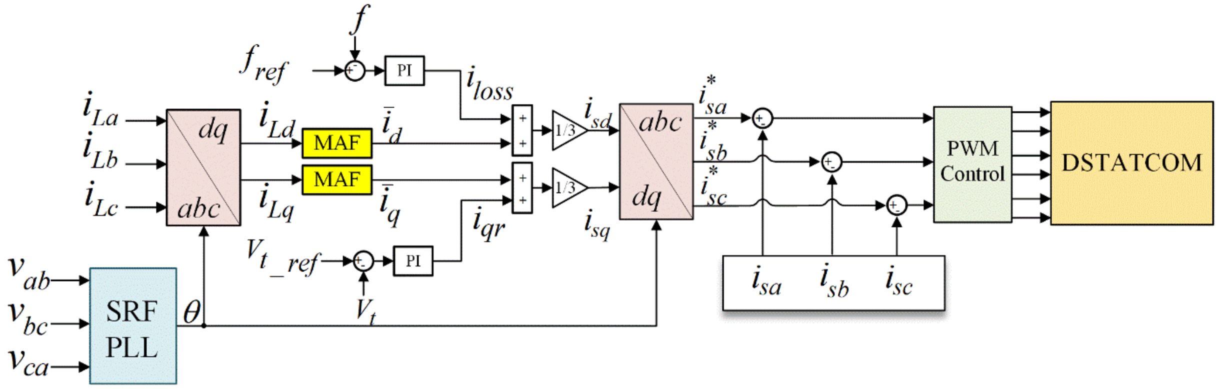

Figure 2 Block diagram of the MAF-based *dq* method

The MAF can act as an ideal LPF in certain cases. Its s-domain and z-domain transfer functions can be expressed as (Golestan et al. 2014)

$$\mathrm{MAF(s)} = \frac{1-e^{-T_\omega s}}{T_\omega s} \tag{1}$$

$$\mathrm{MAF(s)} = \frac{1}{N}\frac{1-z^{-N}}{1-z^{-1}} \tag{2}$$

where T_ω and N stand for window-length of MAF and MAF's order, respectively. The MAF's order N is defined as f_sT_ω, where f_s is the sampling frequency. Using (2), the block diagram of MAF for digital implementation can be easily obtained, as illustrated in Figure 3. As demonstrated, its simple structure facilitates straightforward implementation in DSTATCOM control based on *dq*-theory.

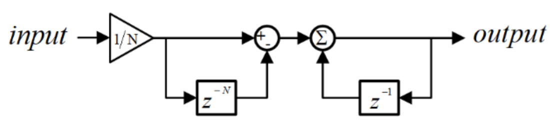

Figure 3 Block diagram of MAF for digital implementation

3.2 *dq*-based Method

The *dq*-based method developed for active and reactive power control in three-phase power systems provides with its fast and stable response to dynamic load changes. This method converts the three-phase quantities in the system to the synchronous reference frame; thus control operations are performed more precisely. The general structure of the method is presented as a block diagram in Figure 2.

When applying the *dq* method, the load currents (i_{Labc}), SEIG terminal voltages (v_{sabc}) and SEIG frequency (f) are measured and used as feedback signals. The measured load currents are transferred to the synchronous reference frame (abc-*dq* conversion) as in Equation (3)

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\omega t & \cos(\omega t-120) & \cos(\omega t+120) \\ \sin\omega t & \sin(\omega t-120) & \sin(\omega t+120) \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{3}$$

The *dq*-axis components of the load current, i_{Ld} and i_{Lq} contain both fundamental and harmonic components. In this study, MAF is employed to extract the fundamental components of the load currents by suppressing the harmonic content. MAF enables it to attenuate harmonics effectively while providing a more stable output with reduced phase delay during transient conditions. The fundamental components obtained at the output of the MAF are defined as follows for use in reference to current calculations:

$$\overline{i_d} = MAF(i_{Ld}) \,,\; \overline{i_q} = MAF(i_{Lq}) \quad (4)$$

In addition, two PI controllers are used in the *dq*-based method. The first one is used to keep the output frequency of the system at a constant and stable level, while the other one is used to regulate the SEIG terminal voltage. In order for DSTATCOM to maintain frequency regulation, it is mandatory to generate a certain level of active current. Otherwise, the frequency of the system may deviate over time and the generator may become unstable.

The active current component i_{sd} used for frequency estimation is calculated based on the frequency feedback in the system. For this purpose, the measured system frequency f is compared with the reference frequency value f_{ref} and the error signal between them is applied to the input of the PI controller.

$$f_{er(n)} = f_{ref(n)} - f_{(n)} \quad (5)$$

The output signal obtained from the PI controller gives the i_{loss} component, which represents the active power demand of the system. This component is calculated as follows:

$$i_{loss(n)} = i_{lossn(n-1)} + K_{pd(n)}\left(f_{er(n)} - f_{er(n-1)}\right) + K_{id(n)} f_{er(n)} \quad (6)$$

The active current component i_{sd}, is calculated using the i_{loss} value generated at the output of the PI controller, as shown in Equation (7).

$$i_{sd} = \frac{i_{loss} + \overline{i_d}}{3} \quad (7)$$

To maintain the SEIG terminal voltage at a stable and desired level, the required reactive power must be accurately determined and supplied. For this purpose, the reactive component of the reference current, i_{sq}, is used to regulate the voltage amplitude. To calculate the i_{sq} component, the peak value of the SEIG terminal voltage must first be determined. The voltage amplitude is calculated as

$$V_t = \sqrt{\frac{2}{3}(V_{sa}^2 + V_{sb}^2 + V_{sc}^2)} \quad (8)$$

The calculated voltage peak value is compared with the reference voltage amplitude (V_{tref}) and the difference between them is applied to the input of the PI controller. The error signal for the terminal voltage amplitude of SEIG is expressed as

$$V_{ter(n)} = V_{tref(n)} - V_{t(n)} \quad (9)$$

In this context, V_{tref} is the reference value determined for the SEIG terminal voltage and $V_{t(n)}$ is the measured instantaneous SEIG terminal voltage. The output signal obtained from the PI controller gives the reactive current component i_{qr}, which is computed as

$$i_{qr(n)} = i_{dn(n-1)} + K_{pd(n)}\left(V_{te(n)} - V_{te(n-1)}\right) + K_{iq(n)} V_{te(n)} \quad (10)$$

Within this control framework, K_{pq} and K_{iq} represent the proportional and integral gains of the PI controller, respectively. Through this structure, the required reactive current component is obtained to maintain the terminal voltage at the desired level. The reactive current component, i_{sq}, is calculated using the i_{qr} value generated at the output of the PI controller, as expressed in Equation (11).

$$i_{sq} = \frac{i_{qr} + \overline{i_q}}{3} \tag{11}$$

The obtained i_{sd} and i_{sq} components are used to calculate the three-phase reference source currents i_{sa}^*, i_{sb}^* and i_{sc}^* via the dq-abc inverse transform.

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_0^* \end{bmatrix} \tag{12}$$

After the reference source currents (i^*_{sabc}) are generated, these currents are compared with the measured instantaneous currents (i_{sabc}) of the SEIG. PWM pulses required are generated according to the error signal obtained. These PWM signals are applied to the IGBT switching elements to provide the required active and reactive power to the system. Thus, DSTATCOM provides precise and fast control to meet the active and reactive power requirement.

4. Results and Discussion

In this section, the performance of the proposed MAF-based dq control algorithm in a DSTATCOM-assisted SEIG system is evaluated. The analysis focuses on the behavior of the system under harsh operating scenarios with nonlinear loads and unbalanced-nonlinear load conditions. These conditions are frequently encountered in standalone applications and have a direct impact on system stability and power quality. Critical performance indicators such as voltage regulation, harmonic content reduction and phase balance are investigated to demonstrate the effectiveness of the proposed method.

4.1 Performance of DSTATCOM-based SEIG under nonlinear load

In the first test scenario, the behavior of the system under nonlinear loads is investigated. Nonlinear loads cause harmonic current generation, which is an important quality problem in power systems. These harmonics can lead to distortion of the voltage waveform, overheating of equipment, reduction of energy efficiency and malfunctions in sensitive devices. In real life, such loads are commonly found in many industrial and commercial applications such as three-phase diode rectifiers, regulated speed drives, welding machines, UPS systems and computer power supplies. Therefore, the ability of SEIG-based systems to maintain stable voltage regulation under nonlinear load conditions is vital for the overall power quality of the system. In this test, the response of the proposed MAF-based dq control structure to harmonic distortions is evaluated.

In Figures 4, the load currents (i_{Labc}), DSTATCOM currents (i_{fabc}), SEIG currents (i_{sabc}), and SEIG terminal voltages (v_{ab}, v_{bc}, v_{ca}) of system for proposed MAF-based dq control approach are shown under nonlinear load. Figure 5 illustrates the amplitude of the SEIG voltages (V_t) and the SEIG frequency (f) under nonlinear load conditions.

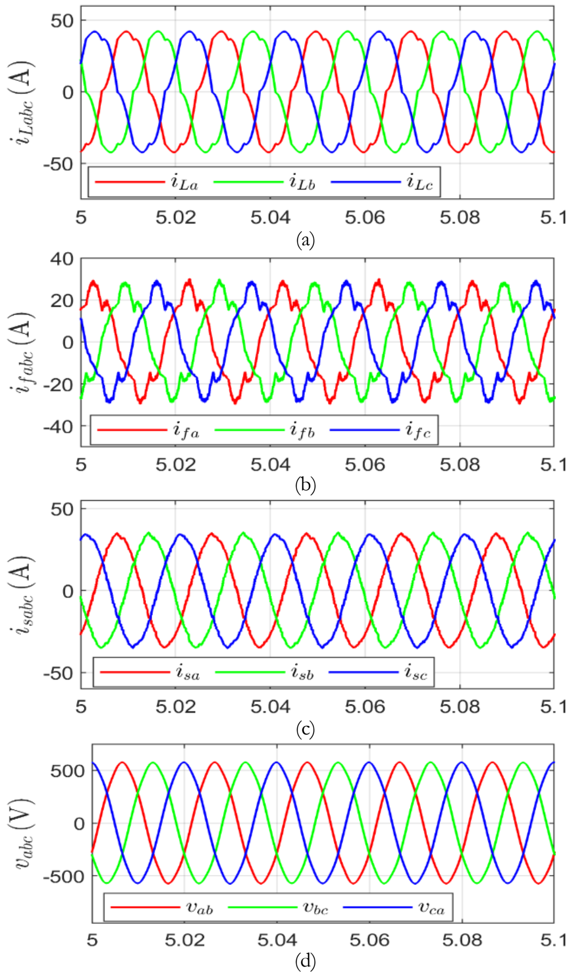

Figure 4 Performance of proposed MAF-based *dq* control method under nonlinear load (a) Load currents, (b) DSTATCOM currents, (c) SEIG currents, (d) SEIG terminal voltages

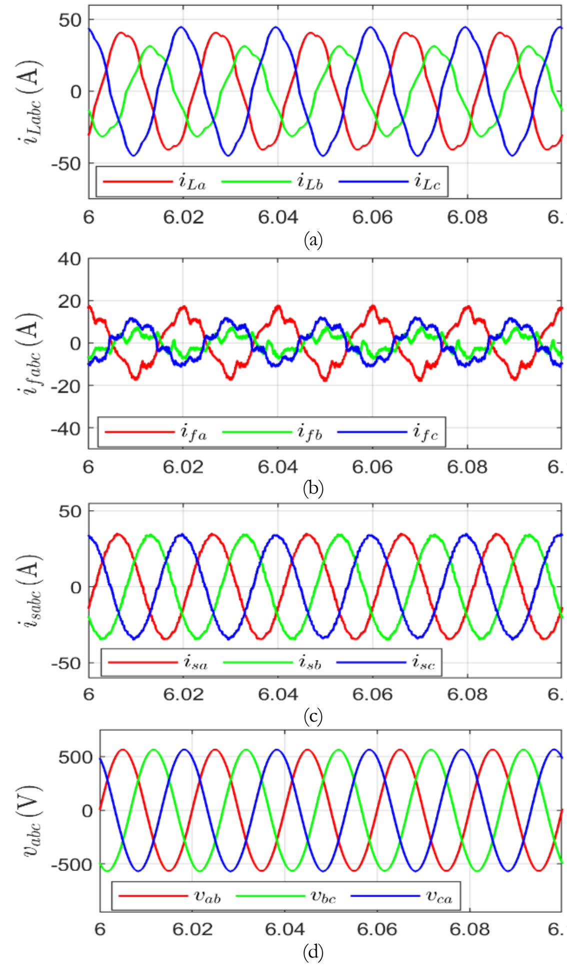

Figure 6 Performance of proposed MAF-based *dq* control method under nonlinear unbalanced load (a) Load currents, (b) DSTATCOM currents, (c) SEIG currents, (d) SEIG terminal voltages

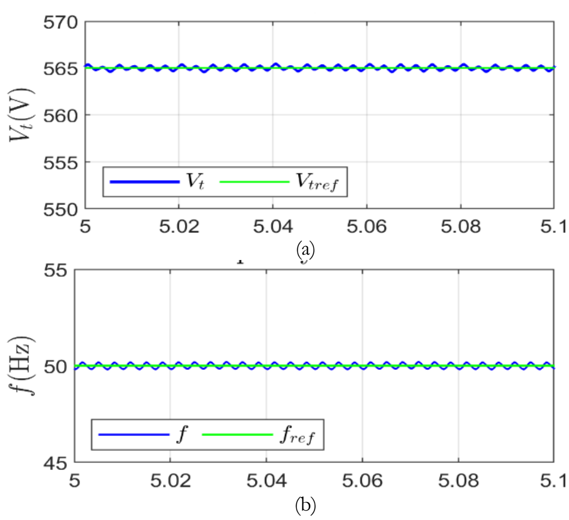

Figure 5 Performance of proposed MAF-based *dq* control method under nonlinear load (a) Amplitude of SEIG voltages, (b) SEIG frequency

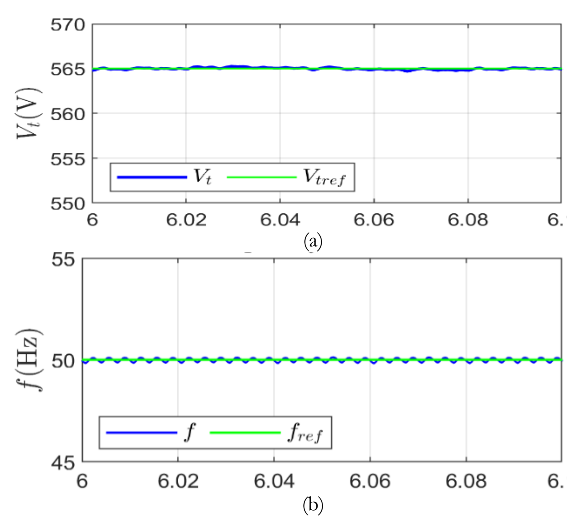

Figure 7 Performance of proposed MAF-based *dq* control method under nonlinear unbalanced load (a) Amplitude of SEIG voltages, (b) SEIG frequency

Figure 4(a) shows the load currents (i_{Labc}) of the system under nonlinear load. The currents in all three phases contain significant and high frequency harmonic components. This clearly shows that nonlinear loads impose significant harmonic distortion on the system.

The phase currents (i_{fabc}) generated by the DSTATCOM are presented in Figure 4(b). These currents are produced to suppress the harmonic components caused by nonlinear loads. As a result, their waveforms are not purely sinusoidal and exhibit differences among phases. Thanks to the proposed MAF-based *dq* control algorithm, the DSTATCOM successfully performs the intended compensation task, thereby reducing the harmonic content in the system currents.

Figure 4(c) shows the output currents (i_{sabc}) by the SEIG. The fact that these currents are smooth, balanced, and nearly sinusoidal, indicating that the disruptive effects on the load side are effectively compensated by DSTATCOM, allowing the generator to produce balanced output currents.

Waveforms of SEIG terminal voltages (v_{abc}) are given in Figure 4(d). In all three phases, the voltages are symmetrical, constant amplitude and close to sinusoidal. This shows that the voltage regulation of the system is successfully achieved. This result shows that the proposed control structure can maintain the voltage quality despite the nonlinear load effect.

The voltage and frequency behavior are evaluated in Figure 5. In Figure 5(a), the peak value of the SEIG terminal voltage V_t is presented in comparison with the reference value V_{tref}. As observed, the terminal voltage is very close to the reference value and contains only low amplitude oscillations. This shows that the voltage regulation is achieved effectively. Figure 5(b) shows the SEIG output frequency. The frequency is kept constant at approximately 50 Hz and no significant deviation is observed except for small amplitude oscillations. This shows that the proposed MAF-based *dq* control algorithm can successfully regulate the system frequency.

4.2 Performance of DSTATCOM-based SEIG under unbalanced-nonlinear load

In another scenario, the system is simultaneously subjected to the unbalanced-nonlinear load conditions. Such complex conditions are among the most challenging scenarios frequently encountered in real world applications and seriously affect the stability and power quality of power systems. While nonlinear loads cause harmonic distortion in the system, unbalanced loads cause current and voltage imbalances between phases. In this test, it is analyzed whether the proposed MAF-based *dq* control method can effectively regulate the SEIG terminal voltage and system frequency in the simultaneous presence of these two disturbances.

Figure 6(a) shows the load currents (i_{Labc}) of the system under the unbalanced-nonlinear load conditions. The current waveforms are not only far from sinusoidal but also contain significant amplitude differences between the phases. This clearly shows that both harmonic and phase imbalance effects are present simultaneously on the load.

The phase currents (i_{fabc}) generated by DSTATCOM are given in Figure 6(b). These currents are generated to suppress load-induced harmonic and distortions and are non-sinusoidal in shape and vary between phases. This is expected because DSTATCOM tries to compensate for the disturbing currents and the output currents are generated accordingly. Thanks to the proposed MAF-based *dq* control algorithm, these compensation currents are generated in the desired form and the overall power quality of the system is improved.

Figure 6(c) shows the SEIG output currents (i_{sabc}), which are balanced, smooth and close to sinusoidal, indicating that the DSTATCOM effectively suppresses load disturbances and the generator output can be maintained without disturbances.

The behavior of the terminal voltages (v_{abc}) is given in Figure 6(d). The voltage waveforms are symmetrical, uniform and constant amplitude in all three phases. This shows that the system can successfully maintain voltage regulation despite the unbalanced nonlinear load conditions.

The voltage and frequency behaviors are evaluated in Figure 7. In Figure 7(a), the peak value of the SEIG terminal voltage is compared with the reference value. The difference was very low, and the terminal voltage could be stabilized at the reference level. The frequency profile shown in Figure 7(b) remains constant around 50 Hz and contains only low oscillations. These results show that the proposed MAF-based *dq* control method performs well in terms of both voltage and frequency regulation.

5. Conclusions

In this study, a MAF-based *dq* control method is proposed for standalone DSATCOM-assisted SEIG systems. The proposed approach enables both voltage and frequency regulation of the SEIG. The *dq*-axis components of the load currents are processed using MAF, which effectively reduces the harmonic content. This enhances the accuracy of reference current calculation and improves the overall system response. The method is evaluated under nonlinear and unbalanced load conditions, and the results demonstrate that the system successfully achieves the desired performance.

Declaration of Ethical Standards

As the authors of this study, we declare that he complies with all ethical standards.

Credit Authorship Contribution Statement

A.S.Ozer: Software, Validation, Formal analysis, Writing -Original Draft, Visualization.
F.Sevilmis: Methodology, Software, Validation, Visualization.
H.Karaca: Investigation, Resources, Writing, Review & Editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

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Data Availability

No datasets were generated or analyzed during the current study.

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