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Alleviation of harmonics for the self excited induction generator (SEIG) using shunt active power filter

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Abstract: The Self Excited Induction Generator (SEIG) is an isolated power source, whose terminal voltage and frequency are controlled by the excitation of capacitance or the load impedance. A new strategy based on an active power filter (APF) for controlling the current and power quality of the self-excited induction generator (SEIG) is also presented in this paper. The proposed active filter proved to play an important role and give good dynamic response and robust behavior upon changes in load parameters. This investigation demonstrated that power average control strategy can facilitate the improvement of the power quality. This control method extracts fundamental (reference) components of the source current for the shunt active power line conditioners for nonlinear loads and unbalanced loads. The shunt APF in conjunction with the proposed controller perform perfectly under different steady state and transient conditions. The simulation results with nonlinear loads and unbalanced loads have showed the effectiveness of the proposed scheme for harmonic reduction in Wind based Power Generation.

Keywords: SEIG, Induction Generator, Harmonics, Shunt Active Filter, Power Electronics

1. Introduction

In recent years, the Self-Excited Induction Generator (SEIG) has emerged as the best electromechanical energy converter to replace the conventional synchronous generator in isolated power generators driven by renewable energy resources: biogas, micro-hydroelectric, wind etc. The main advantages of the SEIG are: low cost, ruggedness, absence of a separate DC source for excitation, brushless rotor construction and ease of maintenance. The fundamental problem with using the SEIG is its inability to control the terminal voltage and frequency under varying load conditions. The analysis of the SEIG under steady-state conditions and imposed speed is already known[1]-[2]. Active Power Filters (APF) are often used in applications where low current harmonics are desirable and/or improvement of quality of energy taken from the power grid are needed with the use of APF, it is possible to draw near perfect sinusoidal currents and voltages from the grid or renewable distributed power sources, where the shape of currents and voltages should be very close to sinusoidal. Another possibility is to balance load currents in different phases which is important in stand-alone power generation like wind turbines. Unsymmetrical load currents e.g. could lead to torque pulsation in generator's shaft and decrease reliability. The currents taken by office consumers have high harmonic contents. It is related to increasing number of loads with rectifier and capacitor, where the current is drawn at the peak of voltage sinusoid. The APF can be used to prevent any kind of harmonic generation. The benefits of using APF could be summarized as: reduction of harmonic content in the grid, reduction of peak value of the current drawn from the grid, reduction of the inrush current taken from the grid, compensation of neutral line current, active power factor correction and transformers are not necessary[3].

2. Description of the Proposed Control

A schematic diagram of the proposed system is shown in "Fig. 1". It consists of a three phase star-connected induction generator driven by an uncontrolled micro hydroelectric turbine. The generator is operated as an SEIG by connecting a fixed terminal capacitor with a value so as to result in rated terminal voltage at full load[4]. When SEIG supplies a non-linear load, the load draws a fundamental component of current and a harmonic current from the generating system which have to be properly controlled. The shunt APF can compensate the harmonic current by continuously tracking the changes in harmonic content. This APF consists of a voltage fed converter with a PWM current controller and an active filter controller that implements an almost instantaneous control algorithm as shown in “Fig.1”. As the input power is nearly constant, the output power of the SEIG must be held constant at all consumer loads. Any decrease in load may accelerate the machine and raise the voltage and frequency levels to prohibitively high values, resulting in large stresses on other connected loads.

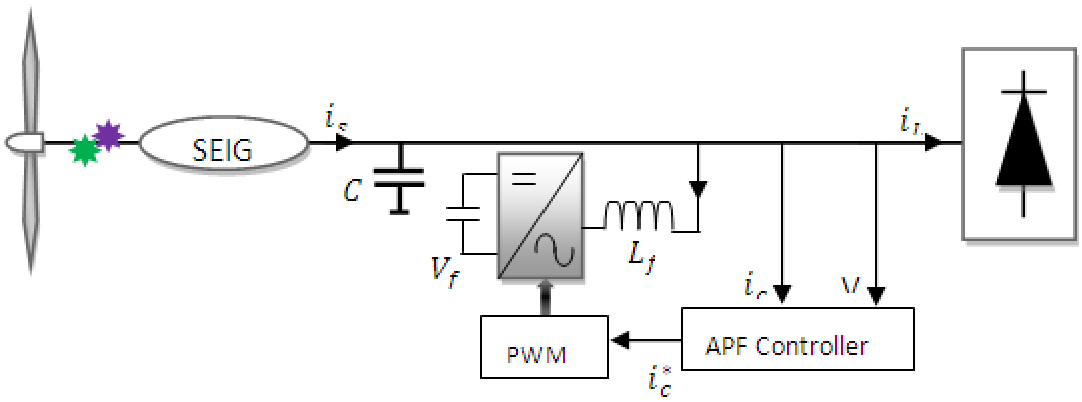


Figure 1. *Block diagram of the APF with SEIG.*

3. Mathematical Model of the Self Excited Induction Generator

A classical matrix formulation using d-q axes modeling is used to represent the dynamics of conventional induction machine operating as a generator. The representation includes the self and mutual inductances as coefficients widely used in machine theory. Using such a matrix representation, one can obtain the instantaneous voltages and currents during the self-excitation process, as well as during load variation. The dynamic model of the three-phase squirrel cage induction generator is developed by using stationary d-q axes references frame and the relevant volt-ampere equations are as[5]-[6]:

$$[V] = [R][I] + [L]\frac{d}{dt}[I] + \omega_r[G][I] \qquad (1)$$

From which, the current derivative can be expressed as:

$$\frac{d}{dt}[I] = -[L]^{-1}\{[R][I] + \omega_r[G][I] - [V]\} \qquad (2)$$

Where $[V]$, $[I]$, $[R]$, $[L]$ and $[G]$ defined below:

$$L = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad G = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & L_m & 0 & L_r \\ -L_m & 0 & -L_r & 0 \end{bmatrix}$$

$$L_s = L_{ls} + L_m, L_r = L_{lr} + L_m$$

$$[V] = \left[V_{ds}V_{qs}V_{dr}V_{qr}\right]^T, [I] = \left[I_{ds}I_{qs}I_{dr}I_{qr}\right]^T$$

$$[R] = diag[R_s\ R_s\ R_s\ R_s] \ \ and\ \ K = 1/(L_m^2 - L_sL_r)$$

3.1. Magnetizing Inductance

The SEIG operates in the saturation region and its magnetizing characteristics are non-liner in nature. Magnetizing current should be calculated in every step of integration in terms of stator and rotor d-q currents as:

$$I_m = \sqrt{(I_{ds} + I_{dr})^2 + (I_{qs} + I_{qr})^2} \qquad (3)$$

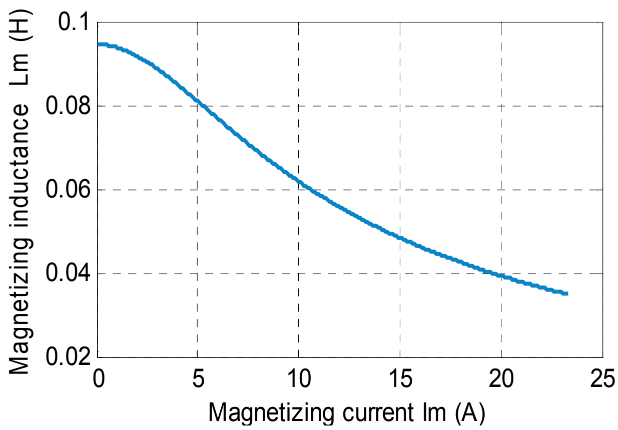


Figure 2. *Variation of magnetizing inductance as a function of magnetizing current.*

Magnetizing inductance is calculated from the magnetizing characteristics which is obtained by synchronous speed test for the machine under test and defined as:

$$L_m = 0.63atan(0.15I_m)/I_m \qquad (4)$$

3.2. Electromagnetic Torque

Developed electromagnetic torque of the SEIG is:

$$T_e = (3P/4)L_m(I_{qs}I_{dr} - I_{ds}I_{qr}) \qquad (5)$$

4. Reference Current Generation Using Average Power Method

The average power method gives accurate results even if the current is distorted. A PLL based unit vector template is used to obtain fundamental component of mains voltage. To get unit vector templates of voltage, the input voltage is sensed and multiplied by a gain equal to $1/vpk$ where vpk is the peak amplitude of fundamental supply voltage. These unit vectors are then passed through a PLL for synchronization of signals. Three phase fundamental components are multiplied by vpk to get fundamental mains voltage. The Power average method needs reduced calculation, since it works directly with $abc-phase$ voltage and line currents. The elimination of the Clark transformation makes this control strategy simple[7][8]. The Power average method presents a minimum rms value to draw the same three phase average active power from the source as the original load current. The control strategy principle for the shunt active power filter based on three-level inverter is illustrated in “Fig 3”.

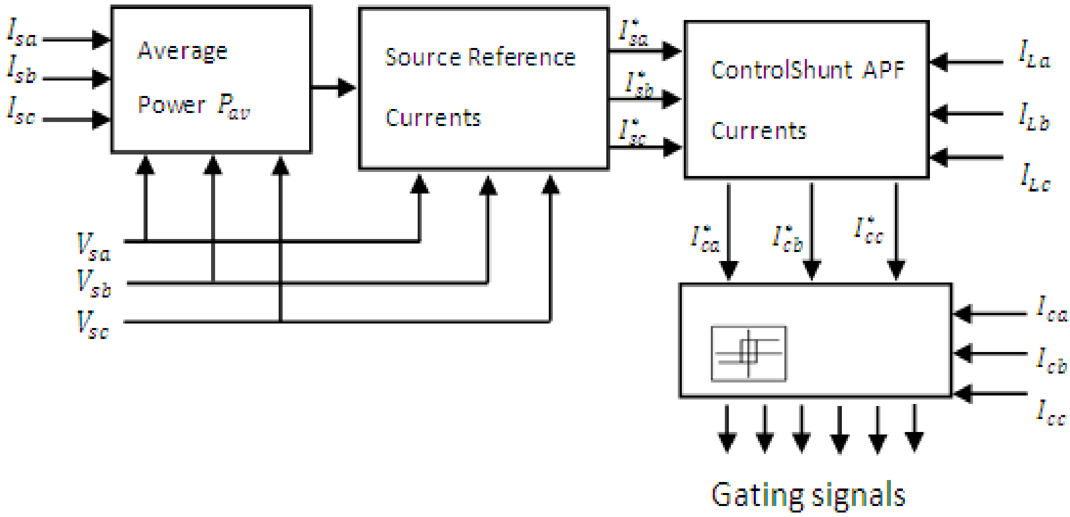


Figure 3. *Block diagram of the proposed shunt active power filter control scheme.6. Analysis and Modeling of the Active Power Filter*

The three phase instantaneous source current can be written as

$$i_s(t) = i_L(t) - i_c(t) \quad (6)$$

The instantaneous source voltage is given by

$$V_s(t) = V_m \sin \omega t \quad (7)$$

If a nonlinear load is applied, then the load current will have a fundamental component and harmonic components, which can be written as:

$$i_L(t) = \sum_{n=1}^{\infty} I_n \, sin(n\omega t + \varphi_n) = I_1 sin(\omega t + \varphi_1) + \left(\sum_{n=2}^{\infty} I_n \, sin(n\omega t + \varphi_n)\right) \quad (8)$$

The reduction of current harmonics in the load current is achieved by injecting equal but opposite current harmonic components at the point of common coupling, thereby cancelling the original distortion and improving the power quality[9].

5.1. Computation of the Average Power

The sensed load currents (iLa, iLb, iLc) and bus voltages (Va, Vb, Vc) through PLL are used to derive the instantaneouspowerp_{ave} as given by:

$$P_{ave}(t) = V_{sa}(t)i_{La}(t) + V_{sb}(t)i_{Lb}(t) + V_{sc}(t)i_{Lc}(t) \quad (9)$$

The three phase instantaneous reactive power in each phase becomes[8]:

$$q_{La} = V_b I_{Lc} - V_c I_{Lb}$$
$$q_{Lb} = V_c I_{La} - V_a I_{Lc} \quad (10)$$
$$q_{Lc} = V_a I_{Lb} - V_b I_{La}$$

The instantaneous active and reactive power delivered to a nonlinear load must satisfy (10) and (11).

$$p_L = p_s + p_c = p_{L1} + p_{Lh} \quad (11)$$

$$q_{fk} = q_{LK}, k = a, b, c \quad (12)$$

Where p_s- Instantaneous active power supplied by the source

p_f- Instantaneous active power supplied by the APF

p_{L1}- Instantaneous active fundamental power of the load

p_{Lh}- Instantaneous harmonic power of the load

q_{LK}- Instantaneous reactive power generated by the APF at phase k.

In order to ensure that the fundamental active power is supplied to the load from the source, the instantaneous reactive power and harmonic power must be compensated by the APF. When considering the compensation of both harmonic and reactive power, P_f is expressed as:

$$P_f(t) = V_{sa}(t)i_{ca}(t) + V_{sb}(t)i_{cb}(t) + V_{sc}(t)i_{cc}(t) \quad (13)$$

5.2. Computation of the Average Power

From (12) and (13), the reference compensating currents are determined as:

$$\begin{cases} I_{sa}^{*} = I_{La} - \frac{p_{L1}}{V_{sa}^2+V_{sb}^2+V_{sc}^2} V_a \\ I_{sb}^{*} = I_{Lb} - \frac{p_{L1}}{V_{sa}^2+V_{sb}^2+V_{sc}^2} V_b \\ I_{sc}^{*} = I_{Lc} - \frac{p_{L1}}{V_{sa}^2+V_{sb}^2+V_{sc}^2} V_c \end{cases} \quad (14)$$

Finally the desired 3-phase references of the APF currents$(I_{ca}^{*}, I_{cb}^{*}, I_{cc}^{*})$ are computed by taking the difference between the three phase instantaneous reference source currents $(I_{sa}^{*}, I_{sb}^{*}, I_{sc}^{*})$ and the actual source currents(I_{La}, I_{Lb}, I_{Lc}) as below:

$$I_{ca}^{*} = I_{sa}^{*} - I_{La}$$

$$I_{cb}^{*} = I_{sb}^{*} - I_{Lb} \quad (15)$$

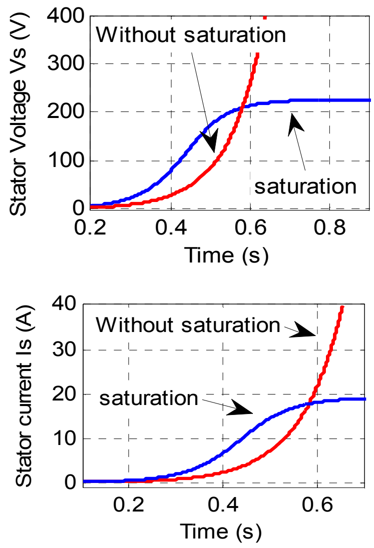
$$I_{cc}^{*} = I_{sc}^{*} - I_{Lc}$$

6. Results and Discussion

The performance of the proposed control strategy is evaluated through simulation using SIMULINK toolbox in the MATLAB. The parameters of SEIG are shown in Table 2. The system parameters values are: source impedance ofR_S, L_S is 0.1 Ω and 1 mH respectively; filter impedance of Rc, Lc is 1Ω and 20mH respectively; diode rectifier R_L, L_L load in steady state: 300 Ω and 100 mH and unbalanced load Rl1, Ll1 :150 Ω and 100 mH, Rl2, Ll2 :75 Ω and 100 mH , Rl3, Ll3: 50 Ω and 10 mH respectively; DC voltage (VDC) is 500V; C_{dc} = 1100µF; Power devices used are IGBT/Diode.

6.1. Performance of Self Excited Induction Generator

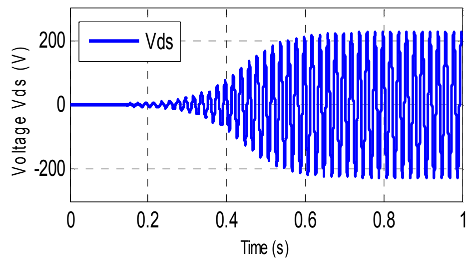
6.1.1. Excitation with and without Saturation



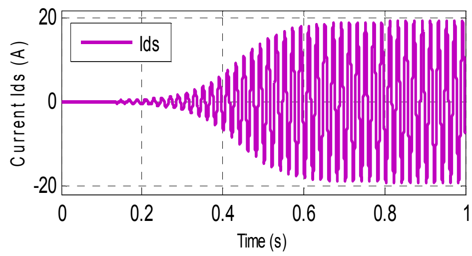
(b)

Figure 4. *Simulation of SEIG with/without saturation*

6.1.2. Excitation with Saturation and no Load



(a)



(b)

Figure 5. *Simulation of SEIG with saturation (a) Stator voltage; (b) Stator current*

When SEIG is excited with capacitance value of C=270µF and rotor speed w_r=1500 rpm, the generated voltage and current attain their steady state values of 380 Volts and 19 A in 0.8 sec as shown in “Fig. 4”.

6.1.3. Variation of Speed

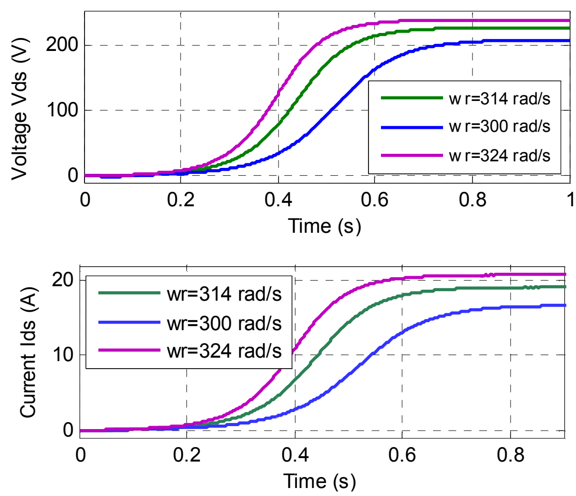


Figure 6. *Simulation of the self-excitation at C = 270 µF with variation of speed (graphs: 1. Stator voltage 2.Stator currents)*

The speed has a direct influence on the voltage for the same magnetizing current, the relation$E' = E\, n'/n$, shows that when the speed of rotation is proportional to the voltage. This is illustrated in Figure 6. And it is not limited by the saturation as in the case of the capacitor.

The speed change also affects the frequency of the voltage, otherwise say if the speed increases with increasing frequency $f_s = n.p/60\,(g \cong 0)$ .In the case of autonomous operation, the speed of the SEIG must be fixed in a restricted range.

6.1.4. Variations of Speed after Full-Excitation

The simulation results presented in Figure 7 shows:

- The transition from speed 314 rad / s to 280rad / s, causes a decrease in the stator voltageand a decrease in the frequencyand stator current delivered by the machine.
- The transition from speed 314 rad/s to330rad/s, causes anincrease in the stator voltageand anincrease in the frequencyand stator current delivered by the machine.

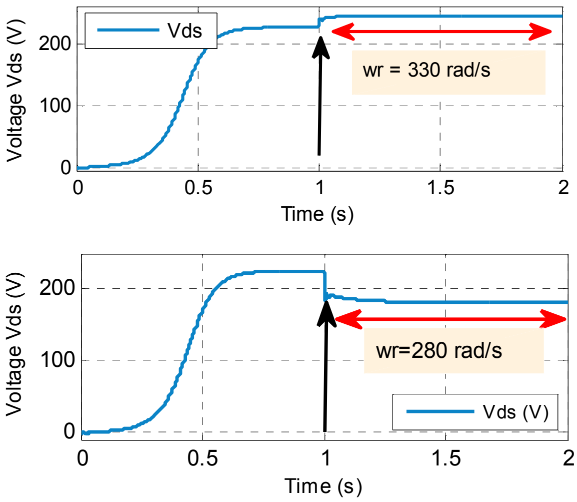
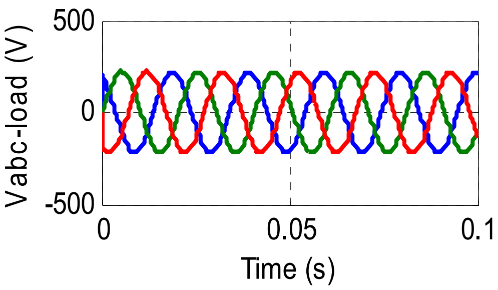
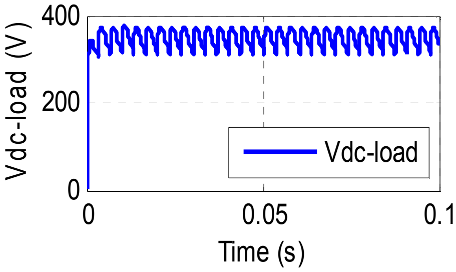


Figure 7. *Simulation of the self-excitation with variation of speed increase/reduction*

7.2. Shunt Active Power System Performance



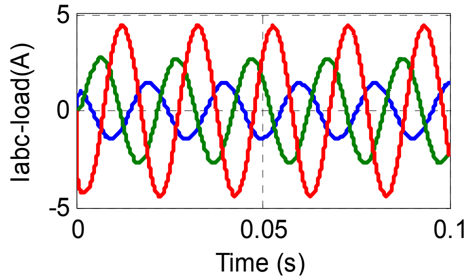
(a)



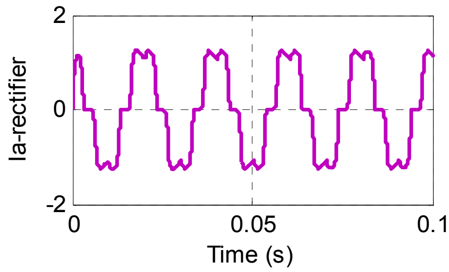
(b)

Figure 8 *(a) Unbalanced load voltage; (b) Nonlinear load voltage*

The unbalanced load RL voltage before compensation is shown in "Fig 8(a)" and the six-pulse diode rectifier RL load voltage before compensation is shown in "Fig 8(b)".



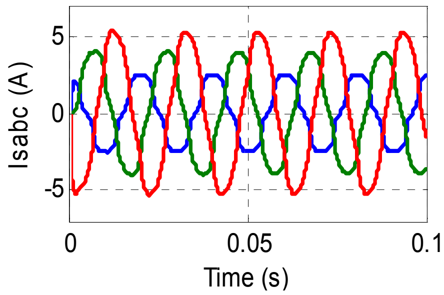
(a)



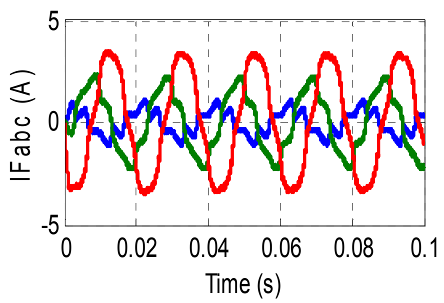
(b)

Figure 9 *(a) Unbalanced load currents; (b) Nonlinear load current.*

The computer simulation results are provided to verify the effectiveness of the proposed control scheme. The unbalanced load RL current before compensation is shown in "Fig 9(a)" and the six-pulse diode rectifier RL load current or source current before compensation is shown in "Fig 9(b)".

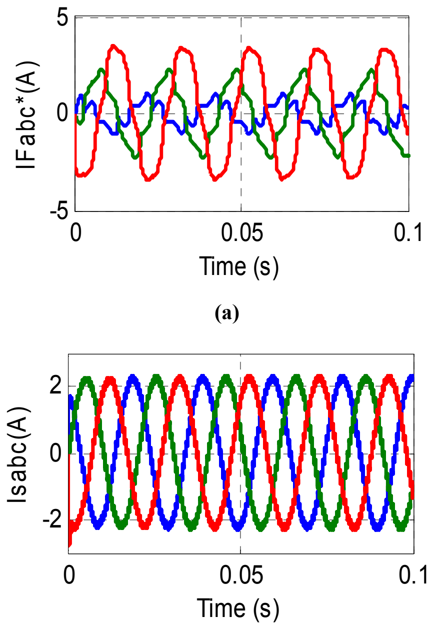


(a)



(b)

Figure 10 *(a) Source current before compensation ;(b) Reference current before APF.*



(b)

Figure 11 *(a) Source current after compensation ;(b) Reference current after APF.*

"Fig. 10 (a)" shows the simulated results of the load currents. The harmonic currents of a nonlinear load and unbalanced load are compensated by the shunt active power filter. The actual reference currents for the three phases are shown in "Fig. 10(b)". This waveform is obtained from the proposed average power controller. The source current after compensation is illustrated in "Fig. 11(b)" which indicates that the current becomes sinusoidal. After active filter operation, the AC-source current only supplies the active fundamental current to the load. The shunt APLC supplies the compensating current that is shown in "Fig. 11(a)". The current after compensation shown in Fig. 11(b) would have taken a shape as shown in "Fig. 10(b)" without APF. It is clearly visible that this waveform is sinusoidal with some high frequency ripples.

The total harmonic distortion is measured using the source current waveform and presented in Table 1 with and without APLC.

Table 1. *Total harmonic distortion (THD %) of source current*

ConditionTHD	(Is)Without APLC	(Is)With APLC
Steady state	23.08%	2.01%

The FFT analysis that was carried out confirms that the active filter brings the THD of the source current down to less than 5% which is in compliance with IEEE-519 standards for harmonics.

8. Conclusion

This paper has presented the implementation of a cage-rotor IG system completely isolated from the utility grid, in order to supply rural sites or isolated areas. In this paper we also discussed the problem of terminal current stabilization of the self-excited induction generator (SEIG) in standalone mode from which a new method of stabilization of the current is used to improve the performance characteristics of the SEIG. This investigation demonstrated also that the generalized Power average control strategy can facilitate the improvement of the power quality. Simulation results are included in order to validate the proposed control technique. It has been shown that the Power average approach additionally maintains the voltage of the capacitor (of the PWM inverter) nearly constant without any external control circuit. Different types of linear and nonlinear loads for reactive power and current harmonics compensation have been connected to the APF to analyze the steady-state and transient performance of the system. The APF has been proved to remarkably eliminate the harmonic and reactive components of load current resulting in sinusoidal and unity power-factor source currents.

Appendix

Table 2. *Parameters of SEIG*

Rated Power	3.5KW
Rated Line to Line Voltage	380 V
Rated line to line Current	14 A
Rated Frequency	50 Hz
Number of poles, P	4
Rated Rotor speed Nn	1410 rpm
Stator Resistance, Rs	0.76 Ω
Stator Leakage inductanceLls	0.003mH
Rotor Resistance, Rr	0.74 Ω

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