

Using of a three-phase four-switch inverter equipped with a variable index PWM to improve the power quality of a wind power plant

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A Harmonic reduction is an essential issue in a grid-connected variable-speed wind energy conversion system to decrease
B the electrical losses of the system and improve the power quality. In this paper, a new Shunt Active Filter (SAF) based on a
S three-phase four-switch inverter is used to improve the output current harmonics of the wind energy conversion system. The
T SAF contains three parts: identification, modulation, and inverter. In the proposed filter, an identification algorithm, which
R is not sensitive to the input source harmonic, is used to cancel out most harmonics impact. Moreover, a modified
A modulation technique based on the identification of the output signal is utilized. In the previous active filters, a three-phase
C six-switch inverter has often been used; however, in the proposed SAF, the number of switches is decreased to four in order
T to decrease the inverter losses. Simulation results confirm the superior performances of the proposed active filter versus the
 prior one for a wind energy conversion system.

Article Info

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I. INTRODUCTION

With the evolution of wind energy conversion systems (WECS) over the last decade, many different control methods have been developed. The control methods developed for WECS are usually divided into two major categories: constant-speed and variable-speed methods [1]. In constant-speed turbines, there is no control over the speed of the turbine shaft. The constant-speed control is an easy, low-cost and more reliable method; however, it has some disadvantages such as the lack of maximum power tracking and reactive power control and higher mechanical stress. In recent years, modern wind turbines have used the variable-speed control to keep the generator torque almost

constant in the presence of wind speed fluctuations and these fluctuations are simulated by changes in generator speed [2]. The variable-speed method brings the following advantages [3]:

- maximum power tracking to harness the highest possible energy from the wind,
- lower mechanical stress,
- less variations in electrical power, and
- reduced acoustical noise at lower wind speeds.

The constant-speed systems rarely include a Power Electronic (PE) converter, except for the compensation of reactive power, while a PE converter plays an important role in modern WECS with the variable-speed control method. The use of the PE converter in variable-speed structures increases the cost and electrical losses [2].

In addition, due to their nonlinear profile and switching action, PE converters are the main source of harmonics in the

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grid that reduce the power quality. In the past, a passive filter was used to reduce PE harmonics. In this kind of filter, the undesired harmonics are canceled out by adjusting passive element values, i.e., the values of inductors and capacitors. The main drawback of passive filters is that they create resonance frequencies that correspond with the system impedance at a frequency below the tuned frequency, which causes current magnification; therefore, it would be less efficient in the reduction of harmonics [4]. To solve this problem, the idea of using an active filter was proposed [5]. In this type of filter, system signals are measured and accordingly a shunt current or series voltage is injected into the line to reduce the system harmonics. An active filter consists of three parts: identification, modulation, and inverter. Among the issues contained in an active filter, the reference signal production methods play an important role in filter designing because of the effect on speed and precision of the filter response [6-8]. These methods can be divided into time and frequency domain methods [9-12]. The time-domain methods are quicker, but frequency-domain methods are more accurate. The time-domain methods, such as $p-q$ transformer (active and reactive instantaneous power theory), do not exhibit good performance in the presence of harmonic sources. However, frequency-domain methods, which are mainly based on FFT, can overcome the above-mentioned problem.

Sinusoidal pulse width modulation (SPWM) is the most commonly used method of modulation. In this paper, a modified modulation method with a variable index is used that is based on the integral of the output signal from the phase detection stage. Also to decrease the filter losses, an inverter with a reduced number of switches is employed in the filter circuit. In other words, the three-phase four-switch inverter is replaced with a conventional six-switch three-phase inverter.

The proposed energy conversion system includes one inverter. The performance of the inverter is affected by three important parameters: the number of the switches, modulation method, and identification approach. The presented identification algorithm does not affect the harmonics of the source.

A Unified Power Controller for Variable-Speed Fixed-Pitch Wind Energy Conversion System is designed [13] that is composed of a new MPPT controller in low wind speed and a proposed constant-speed and constant-power controller in high wind speed. Moreover, a linear quadratic regulator control active power conditioner is implemented for effective source utilization and voltage regulation in low-power WECS [14]. A boost converter is used in the proposed controller. As well, intelligent control of grid-connected AC-DC-AC converters for a WECS based on T-S fuzzy is performed [15]. Further, reducing harmonic instability and resonance problems in wind farms are solved [16-17].

The present paper uses both four- and six-switch inverters.

Furthermore, either sine pulse width modulation (SPWM) or variable index pulse width modulation (VIPWM) is employed. Finally, in addition to the reduction of the current harmonics, the voltage harmonics are reduced. The second one is the lateral advantage. All subjects investigated in this paper are illustrated in Fig.1.

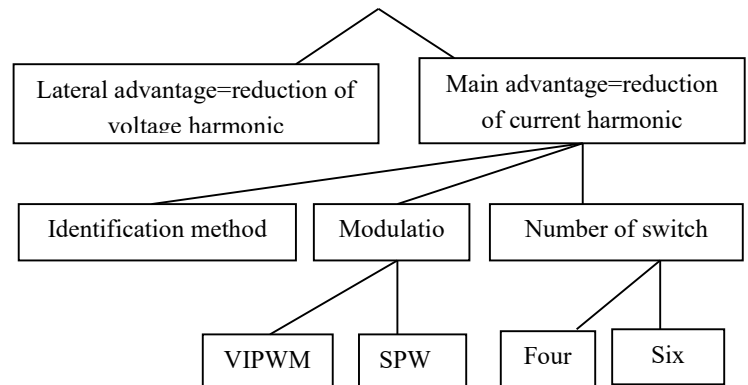


Fig. 1. All subjects investigated in this paper

The use of the VIPWM method in the modulation stage and four-switch inverter are our innovations to improve wind turbine power quality.

Section 2 describes the proposed system. The SAF is explained in Section 3. Section 4 discusses new suggestions to improve system operation. The simulation results are presented in Section 5. Finally, Section 6 provides some conclusions for this research.

II. SYSTEM UNDER STUDY

The literature has talked about four configurations of wind energy conversion systems (WECS) based on the type of electrical generator and PE converter as follows:

- Squirrel cage induction generator with a soft starter
- Wound rotor induction generator with a rotor variable resistance and a soft starter
- Doubly fed induction generator with a power electronic converter
- Permanent magnet synchronous generator (PMSG) with a power electronic converter

Looking from another perspective, wind turbine configurations can be divided into three configurations in terms of the application of PE converters in the WECS: directly connected to the grid without any PE converter, connected via a full-scale PE converter, and connected via a partially-rated PE converter. The generators and PE converter configurations most commonly used in wind turbine systems are discussed below.

The PMSG rotor and stator are connected to the wind turbine and PE converter, respectively.

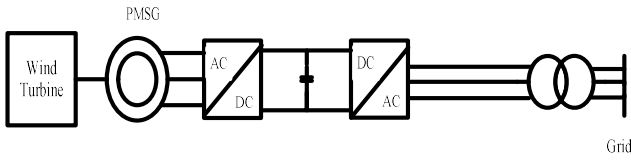


Fig. 2. Wind turbine systems based on PMSG and power electronic converter

The wind turbine, permanent magnet generator, and ac-to-dc converter (rectifier) are the main parts of the system that produce harmonics. In order for the harmonic analysis, the wind turbine is disconnected from the grid, i.e., it works in an islanding mode [3] which is shown in Fig. 3. The SAF used for harmonic reduction is described below.

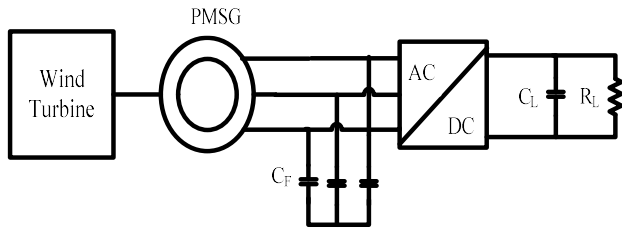


Fig. 3. The studied wind energy conversion system

III. SHUNT ACTIVE FILTER

SAF consists of three stages: identification, modulation, and inverter. In the identification box, line parameters are sampled and accordingly appropriate reference signals are generated. In the modulation stage, to drive the switches an appropriate signal is produced. In the last section, the electrical inverter creates signals proportional to the reference signal for injecting into the transmission line in order to decrease the current harmonics. Fig. 4 shows the SAF block diagram connected to a power system.

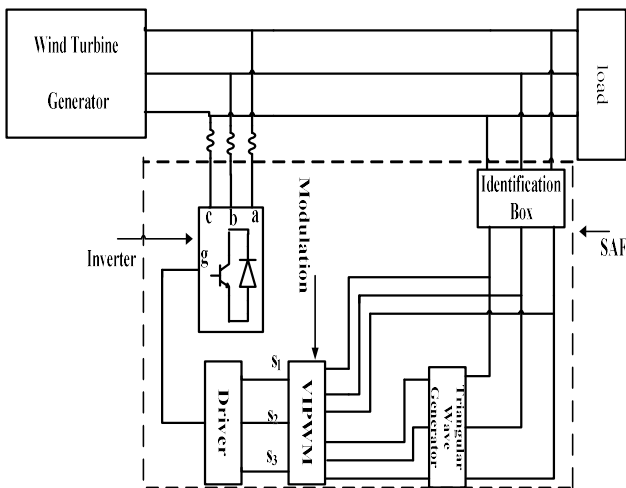


Fig. 4. The diagram of the shunt active filter block

A. Identification Method

The reference current production methods are divided into two categories: time domain and frequency domain. Time domain methods, such as the $d-q$ transform (synchronous reference frame) and $p-q$ transform (instantaneous active and reactive power theory) are based on measuring the three-phase transforms, while the frequency domain methods are based on the fast Fourier transformer (FFT). Time domain methods are fast, while frequency domain methods are more accurate [8]. It has been established that the performance of using instantaneous active and reactive power theory is not proper in the presence of harmonic sources [18].

The power can be calculated as follows:

$$\begin{cases} P = 3 \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \{ V_j^+ I_i^+ \cos((i-j)\alpha + \phi_i^+ - \psi_j^+) + V_j^- I_i^- \cos((i-j)\alpha + \phi_i^- - \psi_j^-) \\ - V_j^+ I_i^- \cos((i+j)\alpha + \phi_i^+ + \psi_j^-) - V_j^- I_i^+ \cos((i+j)\alpha + \phi_i^- + \psi_j^+) \} \\ q = 3 \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \{ -V_j^+ I_i^+ \sin((i-j)\alpha + \phi_i^+ - \psi_j^+) + V_j^- I_i^- \sin((i-j)\alpha + \phi_i^- - \psi_j^-) \\ + V_j^+ I_i^- \sin((i+j)\alpha + \phi_i^+ + \psi_j^-) - V_j^- I_i^+ \sin((i+j)\alpha + \phi_i^- + \psi_j^+) \} \\ P_o = 3 \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \{ V_j^o I_i^o \cos((i-j)\alpha + \phi_i^o - \psi_j^o) - \cos((i+j)\alpha + \phi_i^o + \psi_j^o) \} \end{cases} \quad (1)$$

The dc power in Eq. (1) can be expressed as follows:

$$\begin{cases} P_{dc} = 3 \sum_{n=1}^{\infty} V_n^+ I_n^+ \cos(\phi_n^+ - \psi_n^+) + V_n^- I_n^- \cos(\phi_n^- - \psi_n^-) \\ q_{dc} = 3 \sum_{n=1}^{\infty} -V_n^+ I_n^+ \sin(\phi_n^+ - \psi_n^+) + V_n^- I_n^- \cos(\phi_n^- - \psi_n^-) \\ P_{o,dc} = 3 \sum_{n=1}^{\infty} V_n^o I_n^o \cos(\phi_n^o - \psi_n^o) \end{cases} \quad (2)$$

The superscripts +, - and 0 represent positive, negative and zero sequences, respectively. In addition, V, I, Φ and Ψ are voltage and current, the initial angle of current and voltage, respectively.

Eq. (2) clearly shows that in the dc power transmission from the source to the load, the harmonics are involved. Therefore, the ac power compensation method cannot reduce the line current harmonics. In other words, the voltage harmonics destroy the method operation. In this paper, a frequency method based on the Band Reject Filter (BRF) is adopted so that the line current signal passes through a BRF with a cut-off frequency equal to the power system fundamental frequency. The output signal of the filter contains all the frequencies, except for the fundamental frequency. Therefore, this signal is a suitable reference for the compensation reference. The BRF method needs only the current sensor, while the active and reactive power method needs both current and voltage sensors. Therefore, from the hardware implementation point of view, the BRF method is cheaper

than the power method. In the next section, two inverter topologies are described.

B. Comparing Three-Phase Four-Switch and Six-Switch Inverter

The structures of a four-switch and a six-switch inverter are depicted in Figs. 5a and 5b, respectively. A four-switch inverter has some advantages over a six-switch inverter, such as reducing the number of switches, interfacing circuits, pulse generator circuits, and low switching losses and real-time computation in the microprocessor. However, increasing the voltage pressure on the circuit insulation and asymmetry outputs are the main disadvantages of four-switch inverters [19]. The unbalancing problem is because phase c is connected to the middle of the dc-link and also it is an uncontrollable out phase. Some solutions to these drawbacks are presented in the next sections. As well as, if this inverter is utilized in the low voltage system, the voltage pressure problem will be solved.

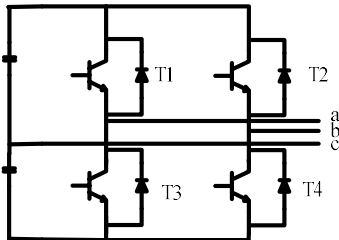


Fig. 5. (a) The three-phase inverter configuration Four-switch

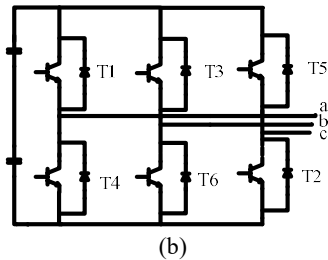


Fig. 5. (b) The three-phase inverter configuration Six-switch

IV. IMPROVING THE FILTER PERFORMANCE

To improve the performance of the SAF, this section presents some suggestions for the inverter configuration and modulation strategy.

A four-switch inverter is employed as a DC/AC converter in the shunt filter. As expressed in the previous section, this replacement has some outstanding advantages, but using four-switch inverters leads to an unbalanced three-phase system. In order to fix this problem, a new method has been used in the following subsection.

Another suggestion to improve filter performance is related to the switching strategy. In the typical PWM modulation, the reference signal is compared with a triangular wave (with constant magnitude). In this paper, a variable magnitude triangular wave proportional to the reference signal is used to decrease the current harmonics. This method is explained in

Section 4.2.

In Ref. [18], SAF is utilized by the six-switch inverter. In contrast, SAF is proposed here by both of the six-switch and four-switch inverter.

A. Symmetry in Three Phase Four Switches Inverter

To solve the unbalanced problem of the four-switch inverter, three reference current signals in the identification stage should be converted into two reference signals [20]. Controlling these two new reference signals results in three-phase symmetry. Since the used inverter is a voltage source inverter, the three-phase current signals should first be converted into a voltage signal. Also, since this filter is connected to the line by an inductor, a capacitor behavior is also needed to cancel out the effectiveness of the inductor. The capacitor voltage is the integral of the capacitor current. Therefore, in order to convert the current signal to a voltage signal and inject the capacitor effect into the line, the current signals are passed through a PI controller to satisfy the above purposes. Then, one of the three voltage signals should be considered as reference and two other signals should be defined according to the reference signal. The best phase for the reference signal is the connected phase to the neutral point in the dc link. In this paper, according to Fig. 5a, phase c is considered as the reference. Consequently, the three signals V_a , V_b , and V_c are converted into two signals, i.e., $V_a - V_c$ and $V_b - V_c$. The phasor diagram of these signals is shown in Fig. 6. Now, instead of controlling the three vectors V_a , V_b , and V_c by six switches (as a balance system), the two vectors $V_a - V_c$ and $V_b - V_c$ should be controlled by four switches (as same magnitude and 60-degree phase differences). It is proved by the following mathematical equations:

$$v_a = V_0 \sin(\omega t) \quad (3)$$

$$v_b = V_0 \sin\left(\omega t - \frac{2\pi}{3}\right) \quad (4)$$

$$v_c = V_0 \sin\left(\omega t + \frac{2\pi}{3}\right) \quad (5)$$

where V_0 is the magnitude of voltage. So, we have

$$v_a - v_c = \sqrt{3}V_0 \sin\left(\omega t - \frac{\pi}{6}\right) \quad (6)$$

$$v_b - v_c = \sqrt{3}V_0 \sin\left(\omega t - \frac{\pi}{2}\right) \quad (7)$$

The modulation function [s] is determined so as to produce a desired set of voltage:

$$\begin{bmatrix} v_a - v_c \\ v_b - v_c \end{bmatrix} = \begin{bmatrix} S_{01} & S_{03} \\ S_{02} & S_{04} \end{bmatrix} \begin{bmatrix} V \\ -V \end{bmatrix} \quad (8)$$

$$S_{01} + S_{03} = 1 \quad (9)$$

$$S_{02} + S_{04} = 1 \quad (10)$$

where V is the half of magnitude of dc-link voltage. The above equation can be solved as follows

$$S_{01} = 0.5[1 + a \sin\left(\omega t - \frac{\pi}{6}\right)] \quad (11)$$

$$S_{02} = 0.5[1 + a \sin\left(\omega t - \frac{\pi}{2}\right)] \quad (12)$$

$$S_{03} = 0.5[1 - a \sin\left(\omega t - \frac{\pi}{6}\right)] \quad (13)$$

$$S_{04} = 0.5[1 - a \sin\left(\omega t - \frac{\pi}{2}\right)] \quad (14)$$

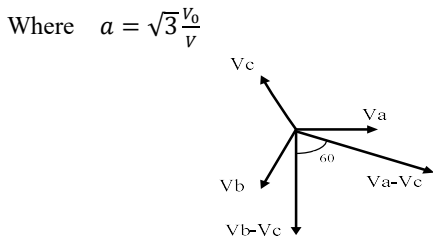


Fig. 6. The desired three-phase voltage vectors and the two resulted vectors

B. Variable Index PWM

In the proposed PWM method, a reference signal is compared with a variable magnitude triangle wave to achieve a better waveform quality which is named Variable Index Pulse Width Modulation (VIPWM) [18]. To generate this signal, an integrator with a reset capability is needed. The operation sequence for phase a (T_1, T_3 in Fig. 5-a) is as follows:

In the positive half cycle, the integration of the reference signal $V_a - V_c$ is first calculated. Then, the output of this integrator is compared with the reference signal. When the reference signal is greater than the triangle signal, T_1 is on and T_3 is off, and when the two signals are equal, T_1 is off and T_3 is on and the integrator is reset. By increasing the integrator output, from zero, T_1 is turned on and T_3 is changed to off again. Fig. 7 shows the performance of this method.

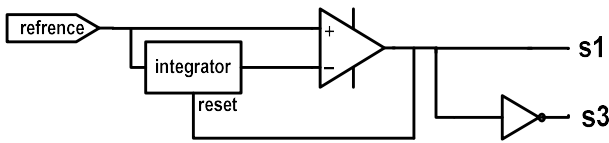


Fig. 7. The configuration of circuitry for transistor driving

In the negative half cycle, the reference signal is compared with the integrator output. When the quasi triangle wave is greater, T_1 is off and T_3 is on. When this signal is equal to the reference signal, T_1 is on and T_3 is off and the integrator is reset. As the output of the integrator decreases from zero, T_1 is off and T_3 is on.

Since the triangle wave magnitude is not constant in this method, it is called variable-index modulation. Using this method with a six-switch inverter, a better result is achieved as compared to the SPWM method as explained in Section 6. Figs. 8 and 9 show the difference in waveforms between SPWM and VIPWM.

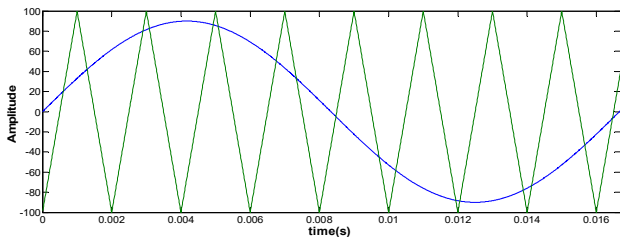


Fig. 8. (a) SPWM modulation with the fixed index $m=0.9$
Triangle and sinusoidal waveforms

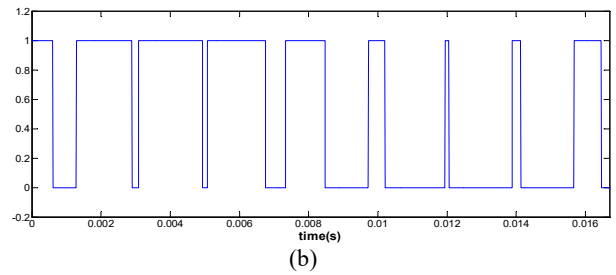


Fig. 8. (b) SPWM modulation with the fixed index $m=0.9$
Logic signal for driving transistor T_1

V. SIMULATION

A system with the parameters given in the appendix is considered according to Fig. 4. There are low and high-order harmonics in the output current of the PMSG machine. In order to reduce the harmonics of this current, compensation with three active filters is done as below:

- Shunt Active Filter with a Six-Switch Inverter and SPWM (SAF-SSI-SPWM)
- Shunt Active Filter with a Six-Switch Inverter and VIPWM (SAF-SSI-VIPWM)
- Shunt Active Filter with a Four-Switch Inverter and VIPWM (SAF-FSI-VIPWM)

Finally, the results are compared with the previous cases.

A. Uncompensated system

Considering the system in Fig. 3 with the parameters presented in Table 1, the output current of the PMSG machine is shown in Fig. 10. The current total harmonics distortion (THD) equals 11.42%; according to the IEEE-519 standard, these harmonics should be reduced.

For harmonic compensation, the active filter with a six-switch inverter is first used and then a four-switch inverter is employed.

B. Harmonic Reduction Using SAF-SSI-SPWM

An SAF-SSI-SPWM is used to reduce harmonic components in WECS. This device can decrease THD to 2.84%. The compensated line current along with its frequency spectra is shown in Fig.11.

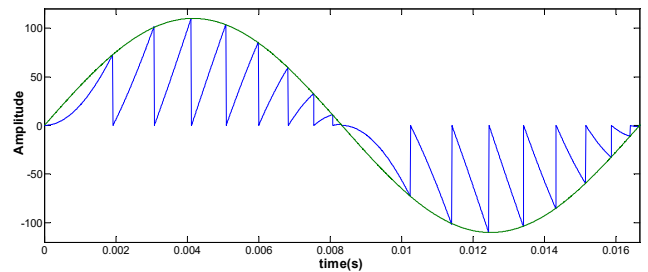


Fig. 9. (a) Modulation with variable index
Sinusoidal and triangular waveforms

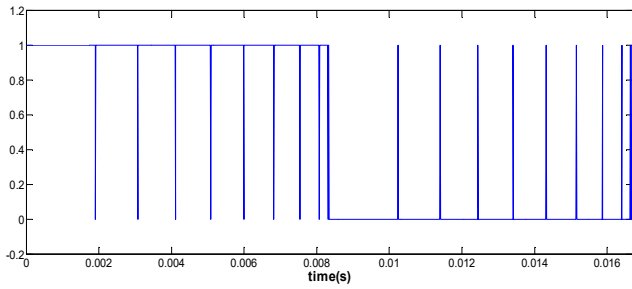


Fig. 9. (b) Modulation with variable index
Logic signal for driving transistor T_1

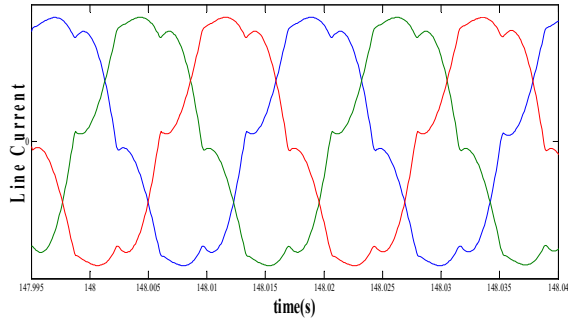


Fig. 10. (a) PMSG output current curve without SAF
Original current waveform

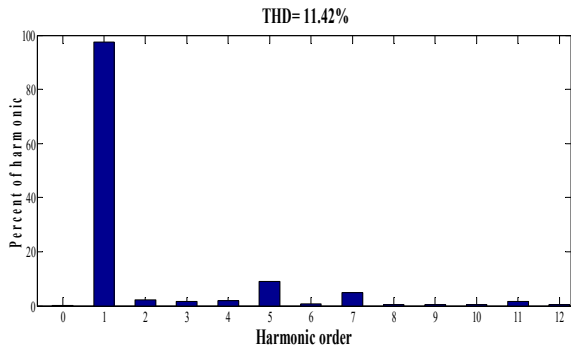


Fig. 10. (b) PMSG output current curve without SAF
Current frequency spectra

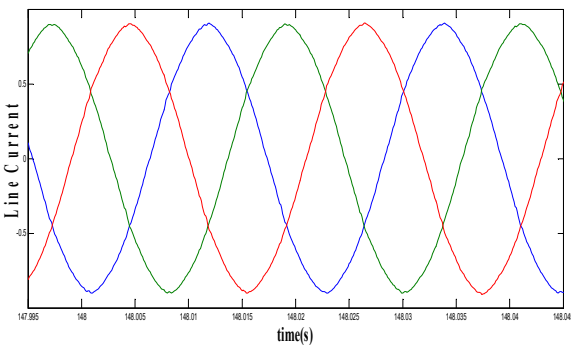


Fig. 11. (a) The output current variation diagram of a wind
power station using SAF-SSI-SPWM
Time domain

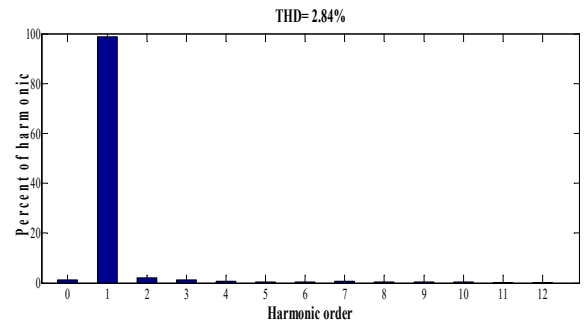


Fig. 11. (b) The output current variation diagram of a wind
power station using SAF-SSI-SPWM

Frequency domain

C. Harmonic Reduction Using SAF-SSI-VIPWM

To reduce the current harmonics, the SAF compensation contains a six-switch inverter used with the VIPWM modulation. The THD of the modified current wave is reduced to 1.86% by using this filter as shown in Fig. 12.

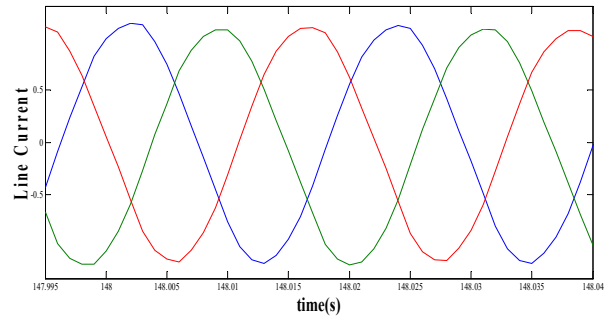


Fig. 12. (a) The PMSG output current curve by
SAF-SSI-VIPWM
Original current waveform

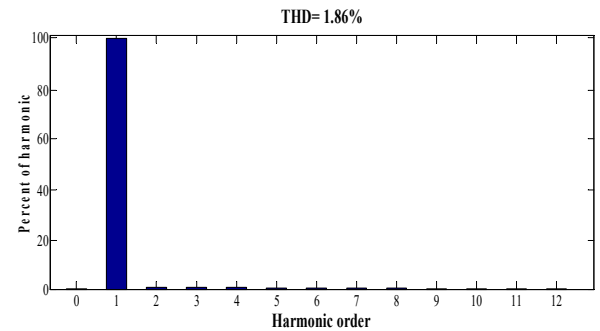


Fig. 12. (b) The PMSG output current curve by
SAF-SSI-VIPWM
Current frequency spectra

D. Harmonic Reduction Using SAF-FSI-VIPWM

If the active filter compensation equipped with a four-switch three-phase inverter (which has symmetry by applying the mentioned method) and VIPWM modulation are used, the current waveform will be modified according to Fig. 13. This filter not only reduces the current harmonics according to the IEEE-519 standard but also satisfies the symmetry in three-phase current, which reflects the effectiveness of the presented method. Reducing the number of switches in an

inverter reduces the capability of the filter. However, this type of inverter satisfies the IEEE-519 harmonics standard. The four-switch inverter has other advantages that are already explained in previous sections. Also, the asymmetry problem is approximately solved by using this inverter.

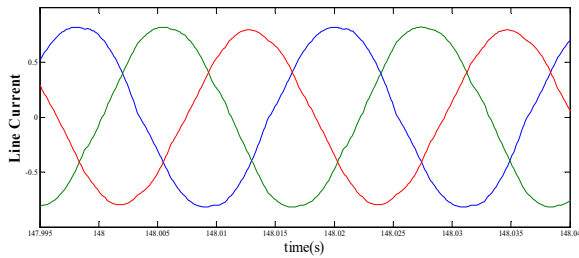


Fig. 13. (a) The output current variation diagram of a wind power station using SAF-FSI-VIPWM

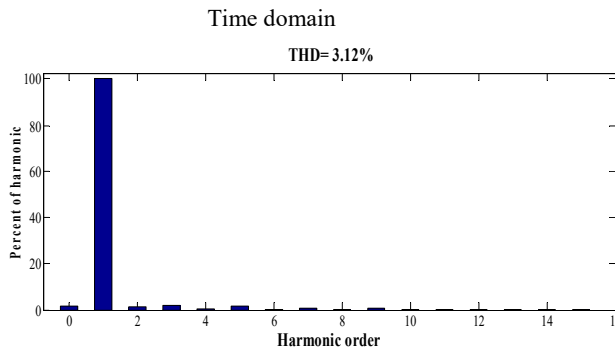


Fig. 13. (b) The output current variation diagram of a wind power station using SAF-FSI-VIPWM

E. Additional Advantages

The main goal in SAF is to reduce current harmonics, but the proposed filter has some other additional advantages. One is the reduction of voltage harmonics (in addition to reducing the harmonic current) in the mentioned application. Although this filter cannot satisfy the IEEE-519 standard in voltage harmonics reduction, it can be considered as a minor advantage. The voltage variation diagram in the uncompensated system is illustrated in Fig. 14 which has 28.9% harmonics.

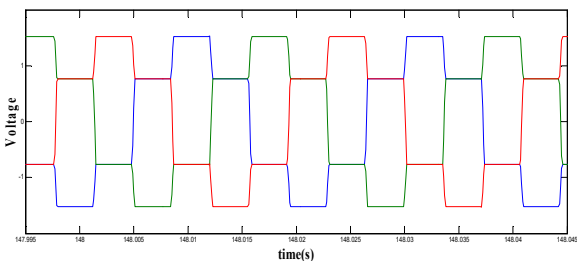


Fig. 14. (a) The PMSG output voltage before compensation Original current waveform

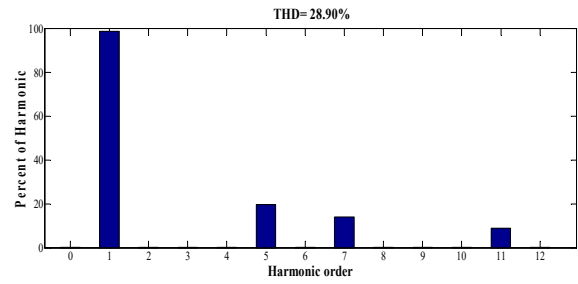


Fig. 14. (b) The PMSG output voltage before compensation Current frequency spectra

If an SAF-SSI-SPWM is used, the THD decreases to 21.4% as shown in Fig. 15. The use of a six-switch inverter and VIPWM modulation leads to a 20.6% reduction of voltage harmonics, while the SAF-FSI-VIPWM can reduce these harmonics to 22.78%. Figs 16 and 17 represent the compensated voltages with the novel modulation strategy using six- and four-switch inverters.

It is worth mentioning that Ref. [3] shows that a six-switch inverter with SPWM modulation reduces the voltage and current harmonics to 20.77% and 2.6%, respectively. Comparing these results with the results of SAF-SSI-VIPWM shows the superiority of this method for modulation. Moreover, the SAF-FSI-VIPWM not only satisfies the IEEE-519 standard but it is also appreciated from economic aspects.

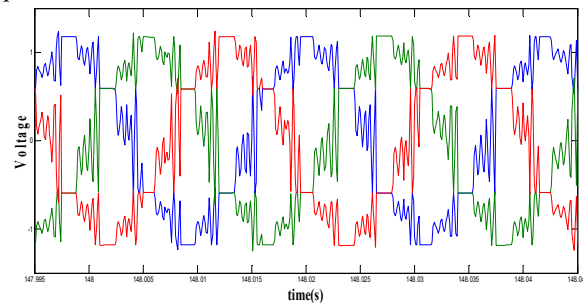


Fig. 15. (a) The output voltage variation diagram of a wind power station using SAF-SSI-SPWM

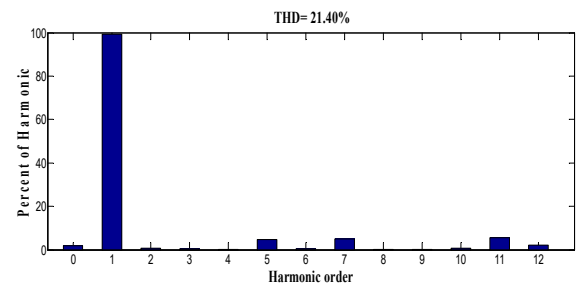


Fig. 15. (b) The output voltage variation diagram of a wind power station using SAF-SSI-SPWM

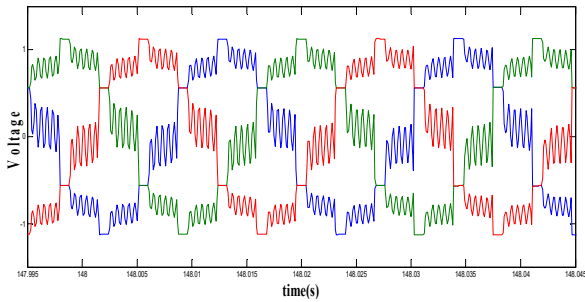


Fig. 16. (a) The PMSG output voltage curve by SAF-SSI-VIPWM
Original current waveform

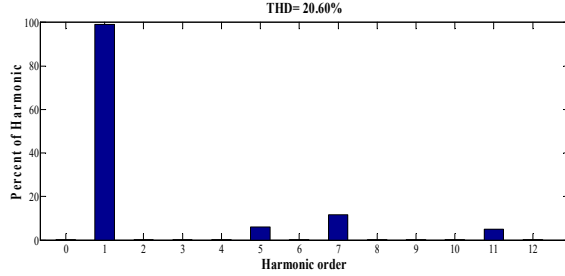


Fig. 16. (b) The PMSG output voltage curve by SAF-SSI-VIPWM
Current frequency spectra

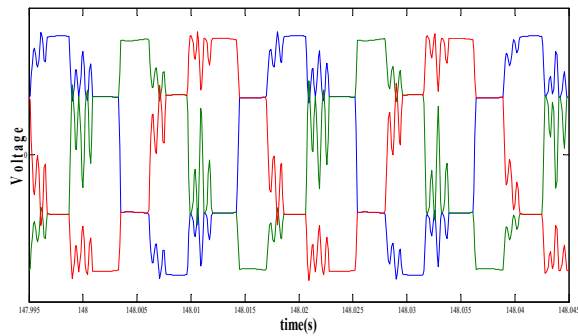


Fig. 17. (a) The compensated voltage diagram using an SAF-FSI-VIPWM; Time domain

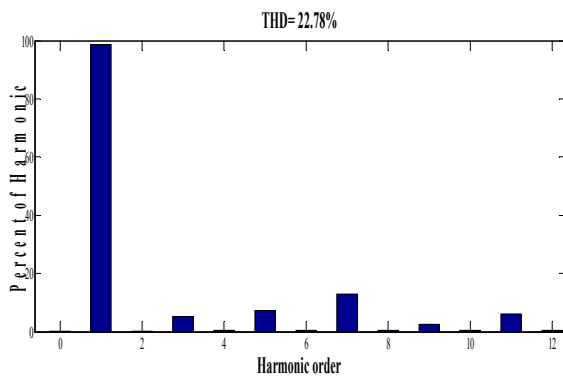


Fig. 17. (b) The compensated voltage diagram using an SAF-FSI-VIPWM ; Frequency domain

Compare all SAFs

The results of applying different SAFs are shown in Table. 1. Moreover, The effect of the two types of inverters used in this manuscript are shown in this Table. As previously mentioned, VIPWM and Inverter six-switch has better results. However, FSI either includes economic consideration or satisfies IEEE-519 standard.

Table. I

The Results Of Applying Different Safs

Type of compensator	Inverter (number of switches)	Modulation	Current's THD %	Voltage's THD %
Uncompensated	-	-	11.42	28.90
SAF-SSI-SPW M	6	SPW M	2.84%	21.4%
SAF-SSI-VIPW M	6	VIP WM	1.86%	20.60 %
SAF-FSI-VIPW M	4	VIP WM	3.12%	22.78 %

VI. CONCLUSION

In this paper, a new shunt active filter is proposed to reduce the current harmonics of a wind power energy conversion. In the identification box of this filter, a method is used which is not sensitive to non-sinusoidal sources. A new modulation method with the variable index is used which is based on the integration of the output signal of the identification box. This method is more useful than the constant index in reducing the current and voltage harmonics. In the inverter side of the filter, instead of a six-switch inverter, a four-switch inverter is used which has a lower switching loss. Decreasing the number of switches in the inverter reduces the capability of the filter, but it can be justified either by the IEEE-519 harmonic standard or from the economic aspects. In addition to reducing current harmonics, improving the voltage waveform quality is an additional advantage of using the proposed filter.

APPENDIX

Wind turbine and PE converter parameters are presented in table2.a. Moreover, active filter parameters are presented in table2.b

TableII.a

Wind Turbine And Pe Converter Parameters

parameter	value
P_t	20kw
V_m	12m/s
J_t	1500
R_s	0.432Ω
L_d	5.24mH
L_q	5.24mH
J	1.954
C_L	5000μF
R_L	6.5Ω
C_F	3.9μF

Table.II.b

Active Filter Parameters

Gain of PI controller	1
Time constant of PI controller	0.001
Center Frequency of band reject filter	60 Hz
Stopping band of band reject filter	20 Hz

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