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ORIGINAL CONTRIBUTION

Novel Control for Voltage Boosted Matrix Converter based Wind Energy Conversion System with Practicality

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Abstract This paper presents the implementation and investigation of novel voltage boosted matrix converter (MC) based permanent magnet wind energy conversion system (WECS). In this paper, on-line tuned adaptive fuzzy control algorithm cooperated with reversed MC is proposed to yield maximum energy. The control system is implemented on a dSPACE DS1104 real time board. Feasibility of the proposed system has been experimentally verified using a laboratory 1.2 kW prototype of WECS under steady-state and dynamic conditions.

Keywords Wind turbine emulator · Wind energy conversion system (WECS) · Voltage boosted matrix converter · Space vector pulse width modulation (SVPWM)

Introduction

Variable speed operation of wind turbines is desirable for wind energy conversion system (WECS) as it yields 10–12 % more output energy with less wind turbine costs. Among existing generators, permanent magnet synchronous generators (PMSG) is considered to be the most suitable generator for variable speed generation because it has distinct advantages in terms of efficiency, weight, size, and reliability. It has better voltage and power capabilities. Also, it does not require brushes and slip rings which increase the maintenance work and cost too.

Power electronics plays an important and decisive role in delivering electrical power from WECS based on PMSG directly to the grid or load. In [1], various power processing topologies have been proposed and investigated from time to time by different researchers. But, all these suffer from the demerits of poor device utilization; produce variable dc link voltage, causes distortion of currents and voltage of generator, poor power factor operation. Out of these configurations, two commonly investigated matured alternatives for wind power generation purpose are ac/dc/ac converter [2–6] and matrix converter (MC) [7–14].

But, recently MC have got lot of attention by the researchers for its application in harassing wind power because of its high merit over traditional converters like free from commutation problems, improved voltage gain with simplified control, compact in size, light weight, high reliability with extremely fast transient response due to absence of dc capacitor.

As a generator, PMSG is considered as better choice in comparison to doubly fed induction generator (DFIG) for variable speed wind turbine because of the requirement of gearbox in case of DFIG, which many times suffers from faults and requires regular maintenance, making the system unreliable. Also, PMSG has various merits like self-excitation capability leading to a high power factor, high efficiency, no gearbox, light weight, high power density, high reliability, high precision and simple control method, except initial installation costs [14–16]. But due to the progress made in the field of permanent magnet materials fabrication, it has extended the PMSG lifetime and decreased the production cost.

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Based on above merits of unidirectional indirect reverse connected MC and PMSG, this work presents experimental investigation of the developed laboratory 1.2 kW prototype of MC based WECS. An adaptive fuzzy logic control along with space vector pulse width modulation (SVPWM) switching have been used to enhance steady-state and dynamic performance under different conditions. Novelty of this work is that reversed indirect MC in voltage-boosted capability with lesser number of switches as compare to traditional MC is experimentally investigated and validated for interfacing PMSG generator with grid or load. To the author's best knowledge, such configuration for WECS applications have been neither addressed nor investigated before.

Proposed WECS

Figure 1 shows the block diagram of the proposed unidirectional indirect MC and PMSG based WECS. The main advantages of the proposed WECS when compared to traditional WECs are low harmonic content, can accommodate large terminal voltage excursions at either side of the MC, any input to output frequency ratio, large frequency variations at either side of the MC, and unbalanced grid conditions. Total harmonic distortion (THD) of output voltages and currents are in consent with the permissible limits of IEEE-519 standard, which severely restricts line harmonic injection.

Wind Turbin Emulator

In this paper, a wind turbine emulator which drives the PMSG is developed for laboratory tests. Figure 2 presents the structure of the wind emulator.

The wind speed changes and load switching conditions are performed using the wind turbine emulator, which consist of 4-quadrant controlled chopper dc drive, whose control is implemented using dSPACE DS1104 real time board. It obtains the wind speed values and by using the turbine characteristics and dc motor speed calculates the torque command of the wind turbine.

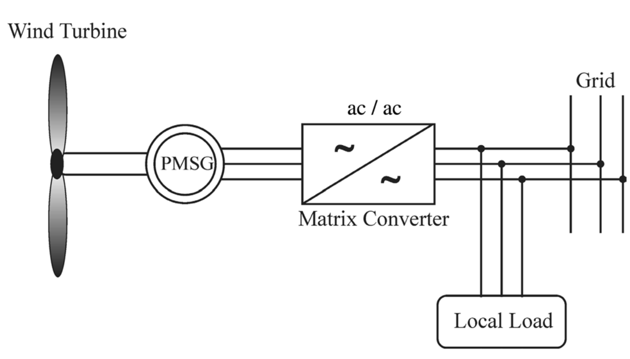

Fig. 1 Schematic diagram of proposed WECS

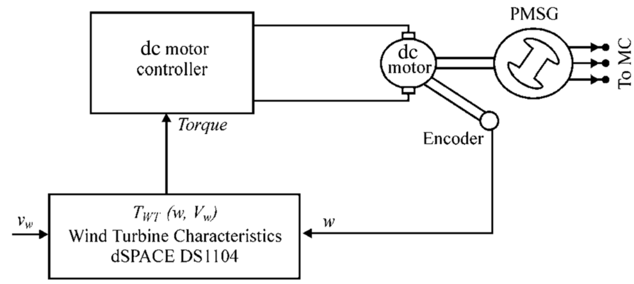

Fig. 2 Wind emulator system

In this way, it is able to reproduce the steady and dynamic behavior of a real wind turbine to the energy conversion system. More details of the developed laboratory prototype of wind turbine emulator have been presented in [12, 16]. At any given wind velocity, maximum power can be captured from the wind, if the shaft speed is adjusted at the value corresponding to the peak power. The novel idea in this paper is to change the angular frequency of PM synchronous generator through SVPWM control of voltage-boosted MC to track the shaft speed corresponding to the maximum turbine power at all times.

Configuration of Voltage-Boosted Matrix Converter

Figure 3 shows the schematic diagram of the unidirectional voltage-boosted indirect MC with twelve switches (clamping circuit is not shown here). As shown, six switches with anti-parallel diodes are arranged as front end voltage source rectifier (VSR), whereas other six switches with series diodes as rare end current source inverter (CSI). It has its power flow from VSR to CSI terminals, which is the reverse direction of traditional MC. This reversal is

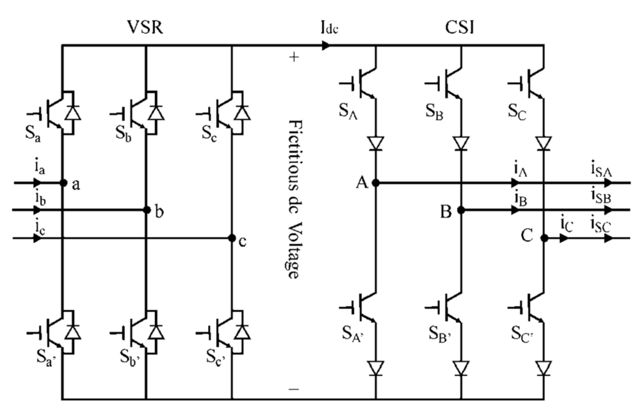

Fig. 3 Schematic diagram of the voltage boosted MC topology

important with aspect to wind generation system as these require voltage boosting of its source with power flowing to grid or local loads.

At any instant, two switches each from upper and lower group of conducts. An active state is formed when two conducting switches are from different phase legs, whereas idle state is formed when conducting switches are from same phase legs.

During active state, power is transferred to load, whereas during idle state circulating current flow within the MC due to shorting of fictitious dc voltage to zero. Space vector representation of CSI and VSR are shown in Fig. 4, where it can be seen that there are total three idle and six active states. The detailed modulation algorithm has been explained in detail by [11–13], and [16–19].

Adaptive Fuzzy Control System

In order to reduce the time-consuming process of the MFs tuning or to ameliorate the performance when it does not satisfy the specification, we can apply an on line-tuned adaptive fuzzy control system (AFCS). An AFCS can adapt to their environment and acquire new knowledge by themselves through learning. A possible arrangement of such a system is the implementation of a fuzzy controller (FC) to adjust the parameters of another FC. This adjustment is accomplished online. The main FCs MFs are tuned online through the supervised-FC, which follows the reasoning of an expert, which would manually tune the MFs.

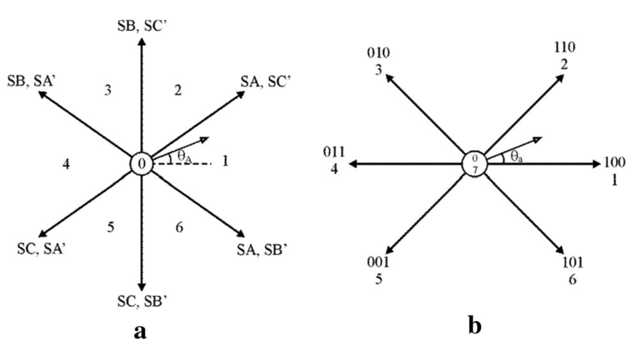

Fig. 4 Space vector representation for **a** CSI of MC and **b** VSR of MC

AFCS are thus very suitable for the control of systems, which are strongly fluctuating, such as wind turbine generation system.

It consists of two main subsystems: the angular frequency and voltage regulator (AFVR), which is active in normal operation mode, and the fault detection control system (FDCS), which is active when short circuit faults take place at the ac grid, as shown in Fig. 5 [11, 12, 16].

In normal operation mode, the main objective of the AFVR is to achieve maximum wind power acquisition from the wind farms, driving the wind turbines to optimum aerodynamic efficiency, whereas during disturbance FDCS becomes active to detect and estimate all the types of disturbances and takes the appropriate action. Various fuzzy rules and structure of the adaptive FC has been detailed in [11, 12]. Figure 6 shows the overall control block diagram of the system that uses the power circuit of Fig. 1.

The system has fuzzy logic controllers for angular frequency and ac voltage regulation, which through the MC manages to yield maximum wind power according to the current wind speed by regulating the angular frequency of the PMSG. The value of ω_{ref} is dynamically approached in real time from FC, using P&O MPPT technique. The algorithm can be explained as below:

$$\text{Pertubtaion}: \omega_{ref}(t) = \omega_{ref}(t-1) + s|\Delta\omega_{ref}|$$
$$\text{Observation}: \Delta P_0 = P_0(t) - P_0(t-1)$$

where $\omega_{ref}(t)$ is the actual optimal angular frequency sampling; $\omega_{ref}(t-1)$, the previous optimal angular frequency sampling; $|\Delta\omega_{ref}|$, the step of optimal angular frequency disturb; P_0, the output power; ω_e, the angular frequency at shaft; ΔP_0, the difference of power; s, the search direction; and $\Delta\omega_{ref}$ is the change in.

This method is achieved by changing the reference value of the frequency by $\Delta\omega_{ref}$ and then monitoring the corresponding change of the output power, ΔP_0. With an increment (or decrement) of ω_{ref}, the corresponding increment (or decrement) of output power P_0 is estimated.

If ΔP_0 is positive with last positive $\Delta\omega_{ref}$, in per-unit value by $L\Delta\omega_{ref\ (PU)}$, the search is continued in the same direction. If, on the other hand, positive $\Delta\omega_{ref}$ causes negative ΔP_0, the direction of search is reversed. MC achieves maximum wind power acquisition from the wind

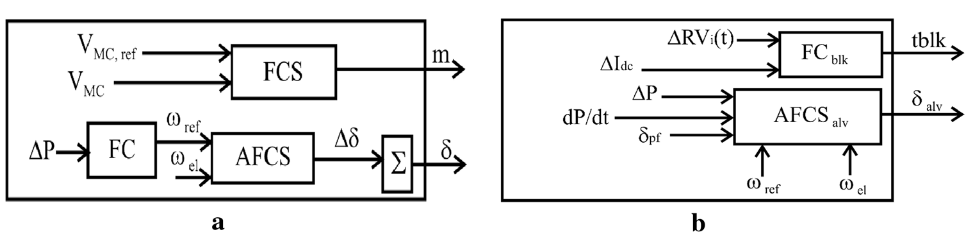

Fig. 5 Proposed adaptive fuzzy control system. **a** Angular frequency and voltage regulator (AFVR). **b** Fault detection control system (FDCS)

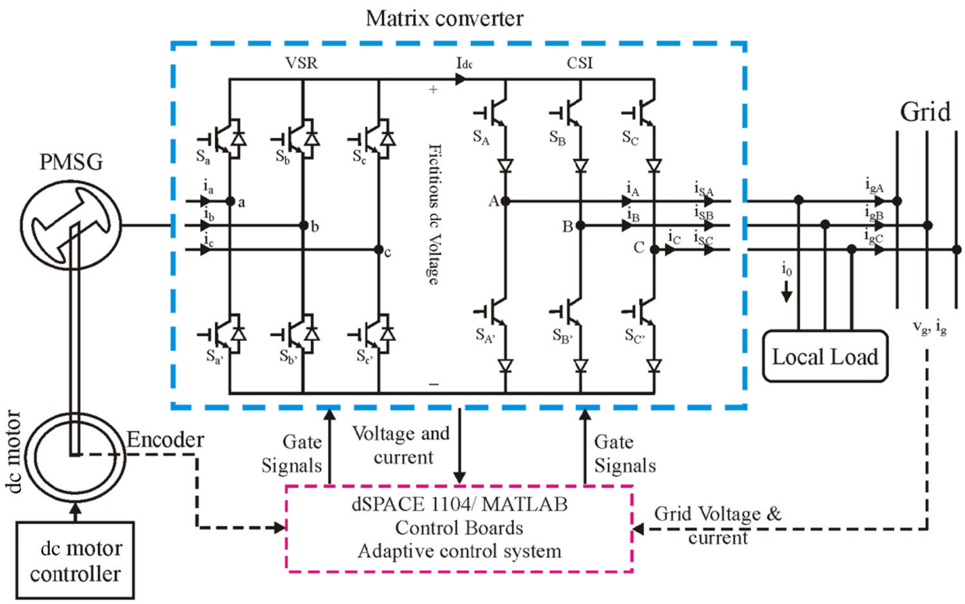

Fig. 6 Overall block diagram of the developed laboratory prototype

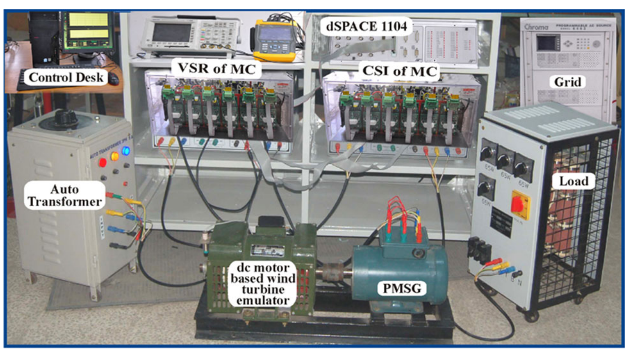

Fig. 7 Schematic of the developed laboratory prototype

turbine by driving the angular frequency ω_e, to its optimal reference value, ω_{ref}. This is accomplished by regulating the active power absorbed by MC, through modulation of phase angle of its SVPWM reference signal.

The variables ΔP_0, $\Delta\omega_{ref}$ and $L\Delta\omega_{ref}$ are described by membership functions and rule table explained in [11, 12, 16] . Finally, this searching method drives ω_{ref} to oscillate near the optimum value for the current wind speed.

MC achieves maximum wind power acquisition from the wind turbine by driving the angular frequency, ω_e to its optimal reference value, ω_{ref}. This is accomplished by regulating the active power absorbed by MC, through the modulation of the signal δ of its SVPWM reference signal, as described in the previous paragraph. So, the electrical angular frequency of generator, ω_e, is monitored and compared to the current reference value, ω_{ref}.

The error is sent to AFCS, which finally generates the SVPWM phase angle δ. For example, when AFCS detects that the value of the electrical frequency, ω_e, is below its current optimal value, it produces a negative value of the signal $\Delta\delta$, resulting in a decrease of the signal δ. By decreasing δ, less power is absorbed from the MC as closed

Table 1 Specifications of the laboratory prototype

Frequency	50 Hz
Wind Turbine Emulator	dc motor drive with armature voltage = 180 V; armature current = 8 A, field voltage = 220 V; field current = 0.5A; rated speed = 1500 rpm; rated Power = 1.5 hp
Generator	PMSG typed with power = 1.2 kW, rated voltage = 230/460 V; current = 2.6/1.2A; number of poles = 4, rated speed = 1800 rpm; frequency = 50 Hz.
Matrix Converter	L_f = 1.5mH, C_f = 12.5 µF, f_{sw} = 10 kHz
Controller Card	dSPACE 1104, 1-GHz processor, 50-bit I/O channels, 36 A/D channels, 8 D/A channels, 6 encoders
Load side filter	L_f = 1.5mH, C_f = 12.5 µF
IGBT module	Semikron make SKM150GM12T4G
Sampling period	Power system = 5e-5 s; Control system = 1e-3 s
Switching frequency	30 kHz

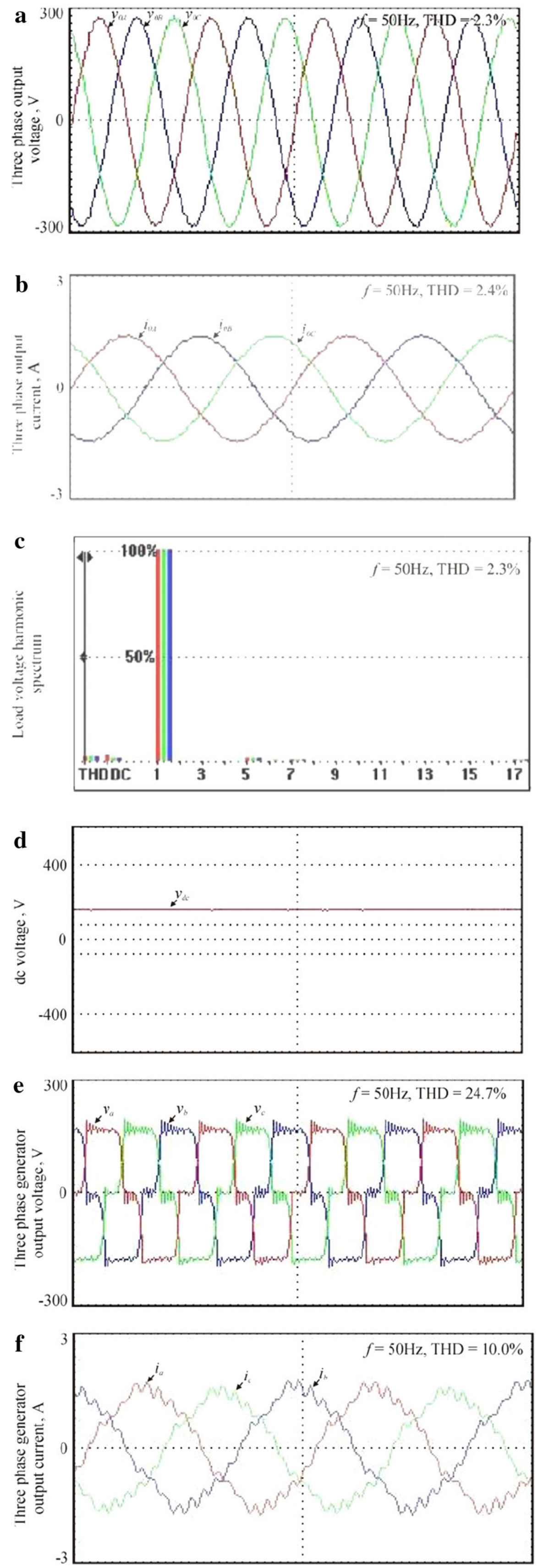

Fig. 8 Experimental waveforms during constant resistive load of 1 kW, 1200 rpm: **a** three-phase output voltage; **b** three-phase output current; **c** load voltage harmonic spectrum; **d** fictitious dc link voltage; **e** generator output voltage; **f** generator output current

loop control commands the decreases of excitation current which in turn reduces the air-gap magnetic field. The energy difference is stored as kinetic energy in the rotors of the machines, increasing the rotor angular frequency, ω_r, which causes a respective increase of ω_e, as excitation current has decreased.

This procedure continues until ω_e takes its reference value. The control strategy leads the wind generation system to capture the maximum power from the wind and make the machine work with higher efficiency by changing the flux in the air-gap. It also controls the terminal voltage. All the control objectives are achieved through improved SVPWM based reversed indirect MC. Control algorithm has been developed in MATLAB/Simulink programming environment using dSPACE DS1104 kit, which is very flexible and powerful system featuring both high computational and comprehensive I/O periphery.

Experimental Results and Discussion

Laboratory 1.2 kW prototype of reversed MC based WECS has been built shown in Fig. 7, using the MATLAB/Simulink and dSPACE DS1104, in order to allow real time control, experimental evaluation of system under different conditions. Table 1 presents the details of the hardware laboratory prototype.

The laboratory prototype is investigated under different input/output conditions like abrupt change in wind speed, disconnection from grid, misfire in the converter, sudden out of one phase, change in load etc. Selected experimental results are discussed here.

Response Under Steady-State

Figure 8 illustrate various experimental waveforms of three phase load voltage, load current, harmonic spectrum for load voltage and current, fictitious dc link voltage, generator output voltage and current for resistive load of 1 kW and at generator speed of 1200 rpm. From experimental result of Fig. 8c, it can be seen that THD for output load voltage is 2.3 %. It can be observed from Fig. 8a, b that three phase output current and voltages are well regulated sinusoidal with almost unity power factor.

A good equilibrium among output voltages and current can be seen. Also, power factor is equal to 0.996 and THD is 2.3 %, which satisfies the power factor demand, and is far better as compared to power factor and THD of about

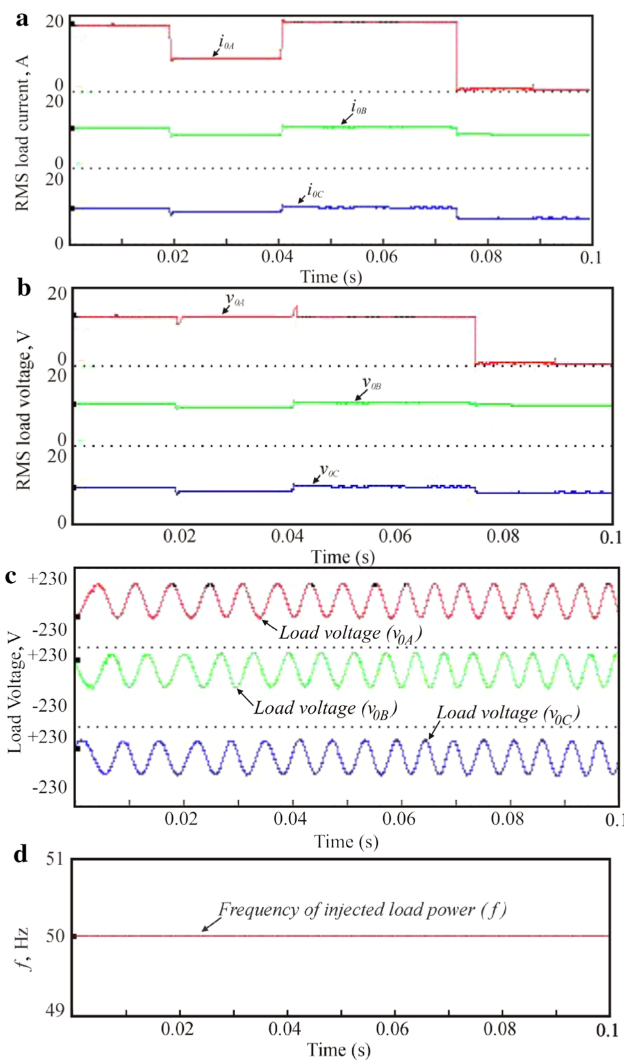

Fig. 9 Experimental waveform during varying load in one phase followed by one phase out condition: **a** RMS load current; **b** RMS load voltage; **c** instantaneous load voltage; **d** frequency of load power

0.94 and 4.25 %, respectively in case of converter topology proposed for wind power applications in [1].

The THD measured for output current and voltage is quite low as per IEEE standard 1547, IEEE-519 and IEC 61727 and thus satisfies the general standards of produced power in terms of voltage and current inside 5 %. It demonstrates the expected improvement when compared with similar works. It is clear that this proposed optimal controller for MC interfaced WECS succeeds in regulating the load voltage and frequency within satisfied limits of 220/400 V and 50 Hz, respectively.

Response During Unbalanced Load Condition

Experimental response of the prototype during critical unbalanced condition, where load of only one phase is varied, followed by one phase out condition is shown in Fig. 9. Initially, load at three phases is balanced with 500 Ω at each phase terminal.

At time t = 0.019 s, the load at phase A is suddenly decreased to 150 Ω and then increased to 500 Ω at t = 0.04 s. At time t = 0.075 s, phase A is switched off suddenly.

Again, it can be seen from the experimental waveform of RMS and instantaneous load voltage in Fig. 9 that proposed adaptive FC is quite capable of making the load voltages balanced even during the worst unbalanced load scenario. It is seen that the controller can regulate the load voltage and frequency quite well under balanced, unbalanced and one phase out conditions. From above experimental performance investigation, it can be concluded that the proposed adaptive FC works very well and shows excellent dynamic and steady-state.

Conclusion

The proposed adaptive fuzzy control along with space vector modulation for laboratory prototype is quite able to maintain the amplitude and frequency of injected load voltage and power. Experimental results validates that developed controller can regulate the output load voltage and frequency quite well during balanced and unbalanced load conditions. Results show that output current and voltage of MC injected to the load satisfies IEC 61727 and IEEE 519 standards. The experimental results illustrates that the controller works very well and shows excellent steady-state and dynamic response with low harmonic characteristics.

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