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A Novel Modified Voltage Oriented Control of an Active Front-End Rectifier used for PMSG based Wind Turbine Systems

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Abstract: This Paper proposes a Novel and Modified Voltage Oriented Control (M-VOC) strategy of an Active Front-End (AFE) Rectifier that can give unity power factor at input side and regulated DC voltage at output side with reversible/bidirectional power flow. The proposed rectifier with M-VOC can find its place in applications like Wind energy conversion systems, DC load for electronic equipment, and adjustable AC drives. Simulation Analysis is done on this M-VOC strategy for an Active Front-End (AFE) Rectifier on MATLAB/ Simulink platform with the verification on the validity of the proposed system. The proposed Rectifier with M-VOC strategy gives good transient/dynamic response for the variations of load at output side. It also gives a pure sinusoidal input current with the elimination of harmonics so that this proposed Rectifier can be used in the case of back to back 2/3 level voltage source converters of wind energy systems that supports bidirectional power flow.

Keywords: Converter control, harmonics, dynamic response, Unity Power Factor, AFE Rectifier, Wind Energy Systems.

I. INTRODUCTION

The main advantages of three-phase rectifiers with diode bridge circuit and a bulk storage capacitor are being robust and simple giving rise to low cost. However, the limitations posed by these diode rectifiers are unidirectional power flow, input side harmonic currents and low power factor. Some of these limitations can be overcome with thyristor based rectifier circuits that introduces the possibility of control of power flow with the control of firing angle given to thyristor. This happens as the output voltage is a function of line voltage as well as firing angle (for controlled rectifiers).[1]-[3] However, thyristor based rectifiers do face limitations like low power factor, harmonic pollution as in case of diode rectifiers. In thyristor based rectifier, as the value of firing angle increases the phase displacement of the input current with respect to the source AC voltage shifts which correspondingly increases the amount of fundamental reactive power. [4]

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At this juncture, a power converter capable of both the active filter operation and Active Front-End (AFE) Rectifier has come into existence. Such a combination operates as a PWM rectifier to supply DC power and at the same time operates as an active filter to supply to the AC line a compensating current equal to the harmonic current produced by the nonlinear load connected to the same AC line. Fig.1 represents a three-phase AFE Pulse Width Modulated (PWM) rectifier with high frequency operation. But, the limitation of AFE rectifiers is its higher cost in comparison with the conventional diode and thyristor based rectifiers. However, AFEs are recommended as it allows the elimination of power factor correction systems and AC harmonic filters at the input side. In recent years, Active Front-End (AFE) rectifiers are playing a vital role in the applications like power supplies for electronic equipment, adjustable DC drives, grid connected renewable sources, battery-chargers, and in various kinds of household appliances etc. [5]

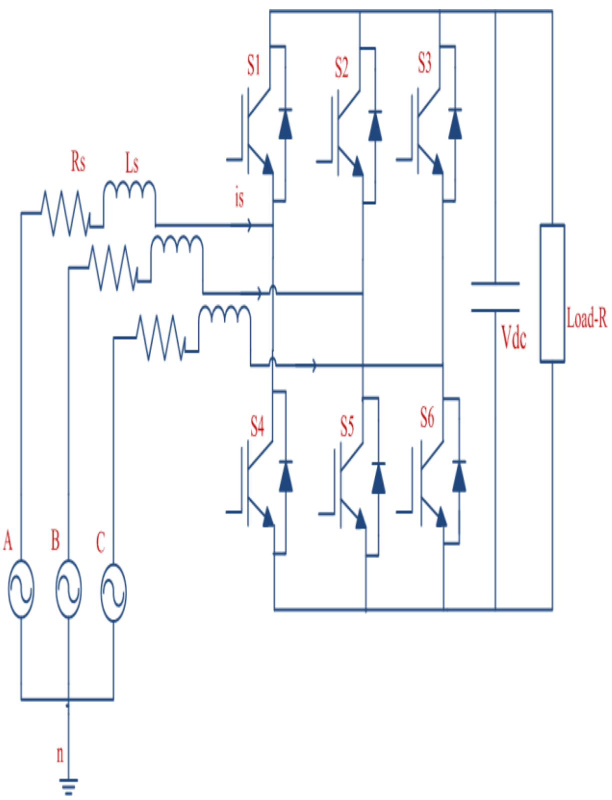

Fig.1 Basic Active Front End Rectifier

A set of research works are carried out with different Control Strategies [6]-[11] that addresses the limitations posed by both the diode and thyristor based controlled rectifiers and also to improve its performance both under open loop and closed loop configurations. One such design is Voltage Oriented Control (VOC) strategy. [12]-[15] In this Control, input active and reactive powers are regulated by input currents which are oriented with respect to the line voltage vector in an indirect way. This Control strategy possesses the advantages like fixed frequency operation, Cheaper A/D converters, and insensitive line inductance changes. However, it has certain limitations like complexity in the control algorithm, coordinate transformation and input power factor. In this paper, a Modified Voltage Oriented Control strategy is proposed and validated by conducting simulation studies with closed loop configuration. The proposed AFE with an IGBT converter, is providing the following functions/ special features in comparison to the existing in the market.

- complete control of harmonics
- complete control of reactive power
- complete energy reversibility
- complete control of DC Bus Bar Voltage

The proposed AFE Rectifier can be used

- in conjunction with Permanent magnet Synchronous generator connected with Wind turbine station as the AFE system is providing unity power factor at the input side as shown in Fig.2.

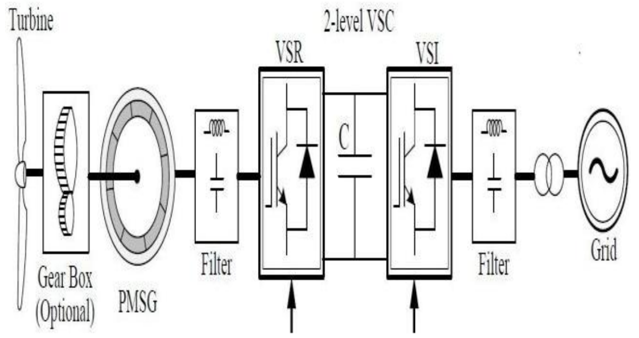

Fig.2 AFE connected to the Wind System-VSR

- to provide direct load for power supplies to feed with electronic equipment as the AFE system gives regulated DC output voltage

- to drive ac motors as the AFE Rectifier system allows the addition of inverter as shown in Fig.3

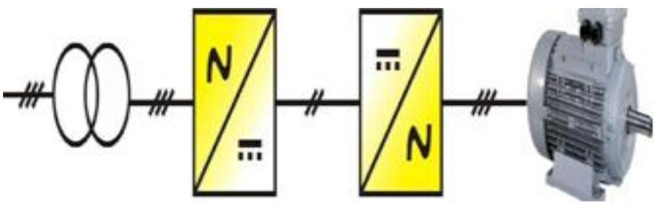

Fig.3 AFE connected to the AC Motor-AC to DC

II. MATHEMATICAL MODELING OF AFE RECTIFIER

The mathematical modeling on the AFE Rectifier as shown in Fig.1. is done and presented below.

The voltage equations for each phase is written as

$$V_{sa} = L_s \frac{di_{sa}}{dt} + R_s i_{sa} + V_{an} - V_{nN}$$

$$V_{sb} = L_s \frac{di_{sb}}{dt} + R_s i_{sb} + V_{bn} - V_{nN}$$

$$V_{sc} = L_s \frac{di_{sc}}{dt} + R_s i_{sc} + V_{cn} - V_{nN}$$

The grid voltage, on considering the space vector definition

$$V_s = \frac{2}{3}(V_{sa} + aV_{sb} + a^2 V_{sc})$$

The grid current dynamics vector equation is obtained as

$$\begin{aligned} V_s = {} & L_s \frac{d}{dt}\left(\frac{2}{3}(i_{sa} + a i_{sb} + a^2 i_{sc})\right) \\ & + R_s \frac{2}{3}(i_{sa} + a i_{sb} + a^2 i_{sc}) \\ & + \frac{2}{3}(V_{an} + aV_{bn} + a^2 V_{cn}) \\ & - \frac{2}{3}(V_{nN} + aV_{nN} + a^2 V_{nN}) \end{aligned}$$

The last term of above equation is taken as zero

$$\frac{2}{3}(V_{nN} + aV_{nN} + a^2 V_{nN}) = V_{nN}\frac{2}{3}(1 + a + a^2) = 0$$

The input current dynamics equation can be simplified on considering grid current and voltage vectors

$$i_s = \frac{2}{3}(i_{sa} + a i_{sb} + a^2 i_{sc})$$

$$V_{afe} = \frac{2}{3}(V_{an} + aV_{bn} + a^2 V_{cn})$$

voltage V_{afe} can be expressed by the below equation on considering the switching state of the converter and the DC link voltage

$$V_{afe} = S_{afe} V_{dc}$$

where V_{dc} and S_{afe} are s the DC link voltage and switching state vector of the rectifier

$$S_{afe} = \frac{2}{3}(S_1 + aS_2 + a^2 S_3)$$

here S_1, S_2, and S_3 are the switching states .

The input current dynamics equation can be rewritten in the stationary $\alpha\beta$ frame as

$$L_s \frac{di_s}{dt} = V_s - V_{afe} - R_s i_s$$

where i_s and v_s are the input current and line voltage vectors and v_{afe} is the voltage generated by the converter

III. PROPOSED MODIFIED VOLTAGE CONTROL STRATEGY-AFE RECTIFIER

The block diagram of proposed Modified Voltage Oriented Control (M-VOC) Strategy is depicted in Fig.4.

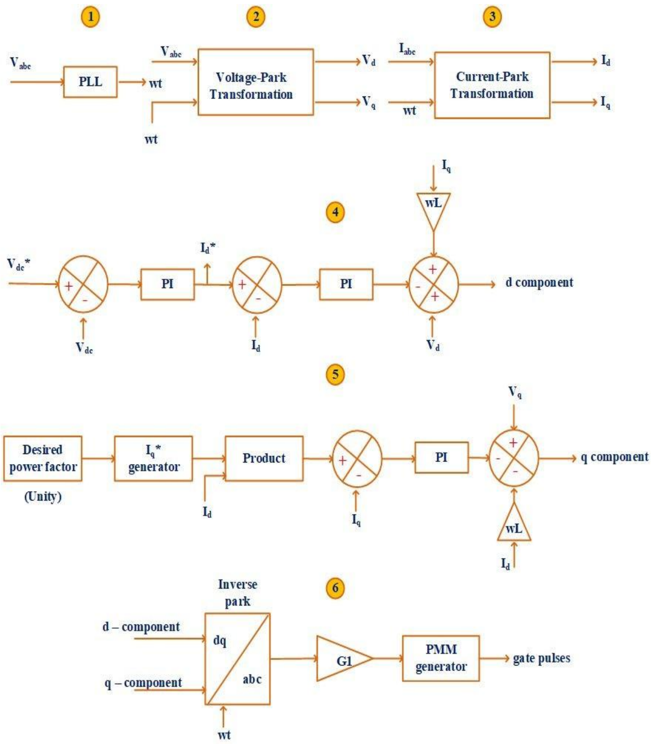

Fig.4 Block Diagram of M- VOC implemented on AFE Rectifier

The explanation of the Modified Voltage Oriented Control (M-VOC) implemented on AFE Rectifier is as follows. The whole control strategy is represented as six stages/parts which is indicated in Fig.4. . In the first part, 3-φ voltages are feeded to a Phase locked Loop (PLL) that synchronizes on a set of variable frequency 3-φ sinusoidal signals to give a desired angle '*wt'*. In second part, by using Park's voltage transformation, 3-φ voltages are converted into direct and quadrature axis V_d and V_q components on considering desired angle '*wt'*. Similarly, by using Pak's current transformation, 3-φ currents are converted in to direct and quadrature axis I_d and I_q components on considering desired angle '*wt'*. First three stages are carried in order to get 3-φ currents in- phase with the 3-φ voltages. In stage 4 , a reference voltage of 600V (V_{dc}^*) is compared with the output obtained from the converter V_{dc}..Two PI controllers with proper K_p and K_i are appended on the error obtained so as to get a voltage signal. This obtained voltage is subtracted from the other two signals as shown in the fourth stage of the above figure to give the d-component of voltage. Now in the fifth stage, the reactive power component is made as zero so as to get unity power factor at input side. The q- component of voltage is obtained on performing the sequence of operation that is indicated in this stage. Finally, in the sixth stage, d-component and q-component of voltage are transformed into abc- frame by implementing Inverse Park's transformation with the consideration of '*wt*'angle. A suitable designed gain is appended to this transformed voltages and is given to the PWM generator. This PWM generator provides six gate pulses to be given to the six IGBT switches that are represented in Fig.1. This proposed control strategy M-VOC gives regulated DC voltage at output side, unity power factor at input side so that bidirectional power flow is possible with AFE Rectifier used in the primary part of back to back PMSG based wind turbine system.

IV. SIMULATION RESULTS AND THEIR ANALYSIS

The specifications considered for AFE Rectifier with M-VOC strategy is given in Table 1.

Table.1 Specifications of AFE Rectifier

Three phase source voltage (V)	V_{rms}= 220*√3
Input frequency (Hz)	50
$R_s(\Omega)$	0.95
L_s (mH)	10
DC link capacitor (µF)	4700
Output DC link voltage (V)	600

For the specifications mentioned a simulation diagram which supports the block diagram shown in Fig.4 is developed on MATLAB/Simulink platform. The simulation is run for 5 seconds and the results are presented as underneath. The 3-φ input rms voltage of 220* √3 having an electrical displacement of 120 degrees with respect to each other phases is shown in Fig.5.

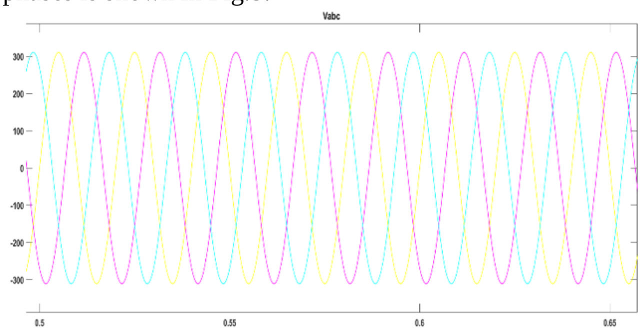

Fig.5 Three phase input supply voltage in volts

Fig.6 represents a pure 3-φ sinusoidal input current waveform with a value of 8 amps in the period of 1st second. This waveform depicts that the harmonic content of the current reduces with THD less than 5%.

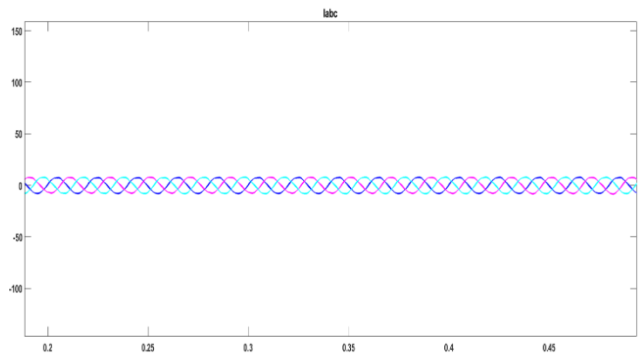

Fig.6 Three phase input current in amperes.

Fig.7 represents input side voltage and current waveform for one phase. This waveform emphasizes that the input current waveform is in phase with the input phase voltage giving rise to unity power factor at the input side to provide very clean energy

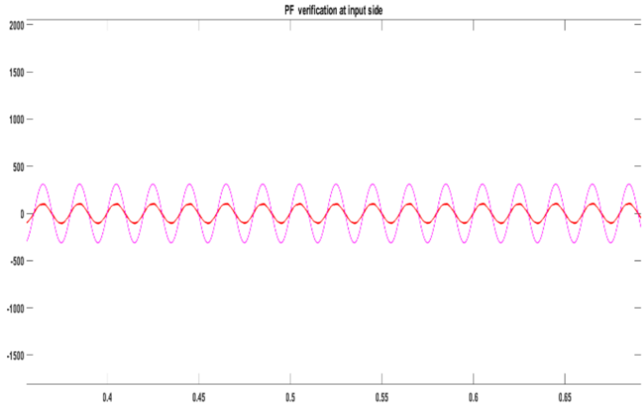

Fig.7 Three phase input side voltage and current waveforms in volts and amperes

Fig.7 also gives the information that there is a complete control of harmonics on implementing M-VOC on AFE Rectifier. This proposed control strategy on AFE gives a complete control of reactive power as it does not exchange reactive power with the line, but exclusively active power.

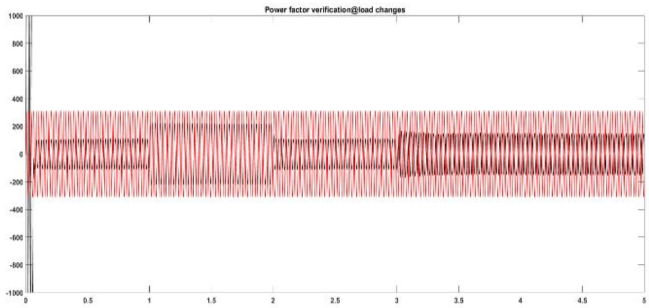

Fig.8 Power factor verification at different loads at different instances of time

Fig. 8 gives the verification of power factor at different loads applied at consecutive 1sec, 2 sec and 3 seconds for the converter. From the waveform it is clear that both voltage applied and current generated are in phase at different loads.

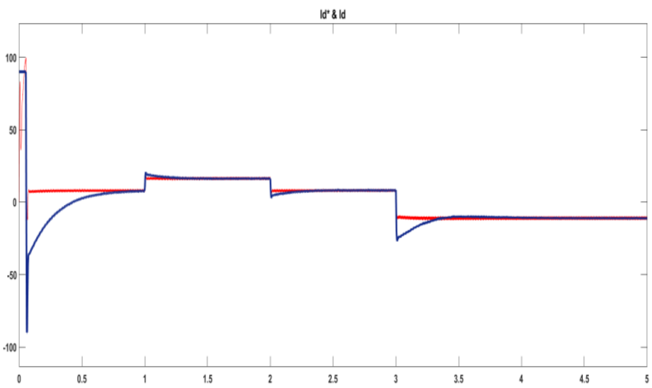

Fig.9. Comparison waveform between I_d^* and I_d

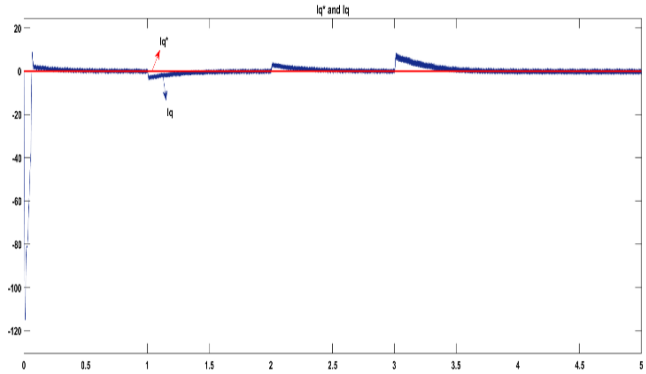

Fig.10. Comparison waveform between I_q^* and I_q

Fig.9 represents a simulated waveform comparing V_d^* and V_d. Fig.10 represents a simulated waveform comparing I_q^* and I_q. It is very clear from Fig.9 and Fig.10 that both the waveforms i.e reference and obtained are running in parallel to each other giving rise to a waveform of output that is given in Fig.11.

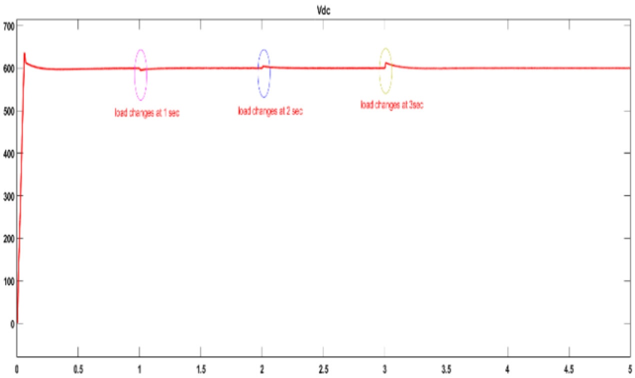

Fig.11 DC output side voltage in volts

Fig.11 represents the DC regulated output voltage of 600V with a very good transient and steady state response. In this waveform, loads are varied at consecutive 1, 2 and 3 seconds. It is noticed from the waveform that there is good regulation of output voltage even if load changes. Since it is observed that there is a regulated voltage , this proposed AFE rectifier can be implemented as a load of power supply for many electronic equipment. From Fig.7 & Fig.11 it is evident that a complete energy reversibility function is existing. Bidirectional power flow is possible between AC mains and DC Bus so that AFE can recover the energy to the mains.

V. CONCLUSION

In this Paper, a Modified Voltage Oriented Control (M-VOC) strategy of an Active Front-End (AFE) Rectifier is proposed. Simulation studies are carried out with results obtained from MATLAB/ Simulink platform. The proposed M-VOC gives unity power factor at input side and regulated DC voltage at output side with bidirectional power flow.

The proposed Rectifier with M-VOC strategy gives good transient/dynamic response for the variations of load at output.

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Kowstubha. P received her four-year B.Tech degree from Sri Venkateswara University in 1995,M..E from Bangalore University in 2003 and Ph.D. from JNTU Hyderabad in 2018. She has 16years of teaching experience. She is a receipant of Gold medal for her research paper by IE(I) published in Springer. She serves as a reviewer for IETE journal. Her fields of interest are Power Electronics, Integrated circuits, and Control systems

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