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Design and Simulation of Three-Phase Voltage Source Based Converter for HVDC Applications

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Abstract

These days wind farms are built far out in the sea, which is advantageous from power generation point of view, but not that lucrative when it comes to their connection to the AC grid. Voltage Source Converter (VSC) based HVDC transmission which uses IGBTs and extruded DC cables is a latest HVDC technology used for low power transmission which easily integrates wind farms and solar farms to the grid. It operates with high frequency PWM in order to get high speed control of both active and reactive power. This paper investigates the operation of pulse width modulated (PWM) based boost rectifier topology operating as a VSC. The system under consideration is analysed under static as well as dynamic conditions of loading with R and RL load.

Keywords: PWM rectifier, VSC, unity power factor.

1. Introduction
Three-phase AC to DC converters are extensively used in many applications such as uninterruptible power supplies (UPS), battery chargers, adjustable speed drives, utility interface with non-conventional energy sources such as solar photovoltaic cells, wind etc. These AC to DC converters can be realized using diode rectifiers or phase-controlled rectifiers. Both of these behave as non-linear loads on the power system. As a result, the current drawn by the rectifier is rich in harmonic contents which distorts the supply voltage and also gives poor supply power factor [1].

In this paper, a three-phase PWM based converter is simulated. The proposed converter works at unity power factor for steady state as well as dynamic conditions for both R load and RL load. Irrespective of any loading conditions up to rated, it maintains constant output voltage at the DC link. The converter is simulated with closed-loop control also.

2. VSC Operating Principle

In fig. 1, the operating principles of a VSC are evident. The DC voltage V_d is monitored and compared to a reference value V_{ref} to generate an error signal which controls the PWM controller. When the DC current I_d is positive, the VSC acts as a rectifier; the DC capacitor is discharged as it feeds the DC load, and the control system will modify the firing angle to import power from the AC system. When the DC current I_d is negative, the VSC acts as an inverter; the DC capacitor is charged from the DC source, and the control system will modify the firing angle to export power to the AC system [2].

The VSC can also modulate the firing of the valves to control the reactive power so that a unity power factor (or any other value, for that matter) can be obtained. The PWM controller generates a voltage V_{gen} with the same frequency as the AC system voltage V_S. By altering the amplitude of V_{gen} and its phasor relationship with V_S, the converter can be made to operate in all four quadrants i.e. rectifier/inverter operation with lagging/leading power factor. Under rectifier operation, the circuit works like a Boost converter, and under inverter operation it works as a Buck converter.

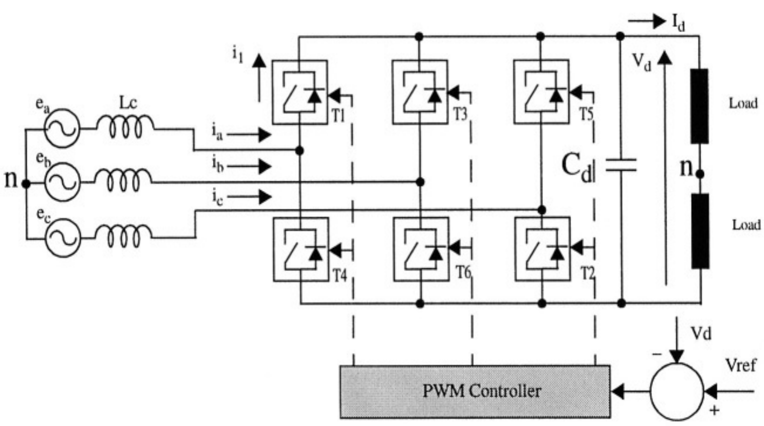

Fig. 1: VSC Operating Principle.

3. SPWM Control

A modulation technique to generate the firing pulses for the VSC switches is necessary. One of the most common methods is the Sinusoidal Pulse Width Modulation (SPWM) technique which uses a triangular carrier wave, as shown in fig. 2. By almost instantaneous change of PWM pattern, the creation of any phase angle or amplitude is enabled. Thus, PWM gives the possibility of separate control of active and reactive power, which makes this technology a very good choice for power transmission.

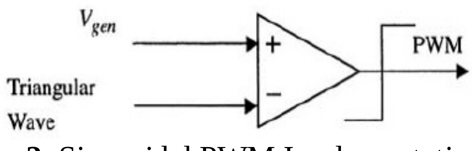

Fig. 2: Sinusoidal PWM Implementation.

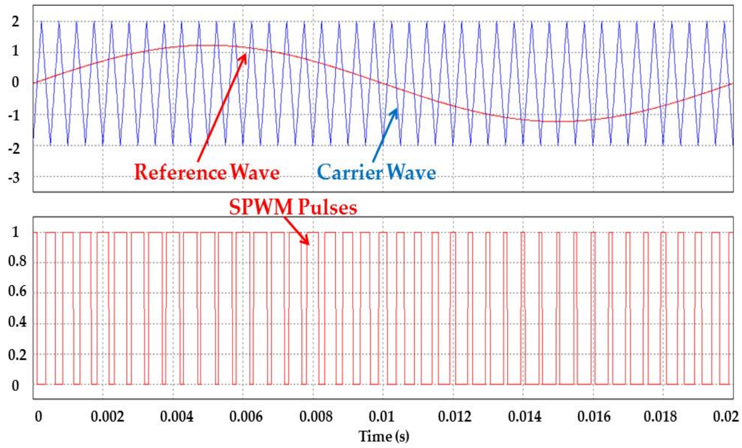

Fig. 3: Waveform showing SPWM pulses.

The width of each pulse is varied in proportion to the amplitude of a sine wave. The gating signals are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency fc. The frequency of reference signal fr determines the inverter output frequency fo; and its peak amplitude Ar controls the modulation index M, and then in turn, the rms output voltage Vo. SPWM technique together with AC voltage control will be used for achieving the desired control for our application [1]. As seen in fig. 3, a sine wave and a triangle wave are compared and the resulting pulses after comparison are fed to the IGBTs.

4. Calculations

The system is considered to be rated at 100 MVA, 100 MW. The various parameters are:

AC Input Voltage:

$$V_{rms} \text{ (line-to-line)} = 39 \text{ kV}$$

Frequency, f = 50 Hz

AC Input Current:

$$I_{ac} = \frac{\quad}{\quad} = 0.91 \text{ kA}$$

Boost Inductance:

$$L = 4.1 \text{ mH}$$

DC Link Capacitor:

$$C_{dc} = 470\ \mu\text{F}$$

$$V_{dc} = 1.4\ V_{ac} = 1.4 \times 39 = 54.6 \text{ kV}$$

5. Simulation and Results for Open Loop System

Fig. 5 shows the DC output waveforms for the open loop system shown in fig. 4. In the simulation, the voltage is sensed from the source and given to the SPWM circuit for comparison. Fig. 6 shows the waveforms of input voltage and current of phase-A which are in phase, indicating unity power factor for an active front end rectifier.

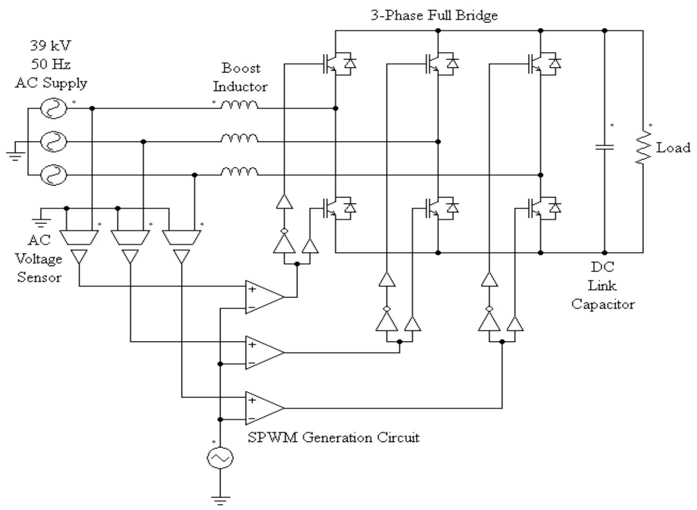

Fig. 4: Open loop simulation of voltage source rectifier

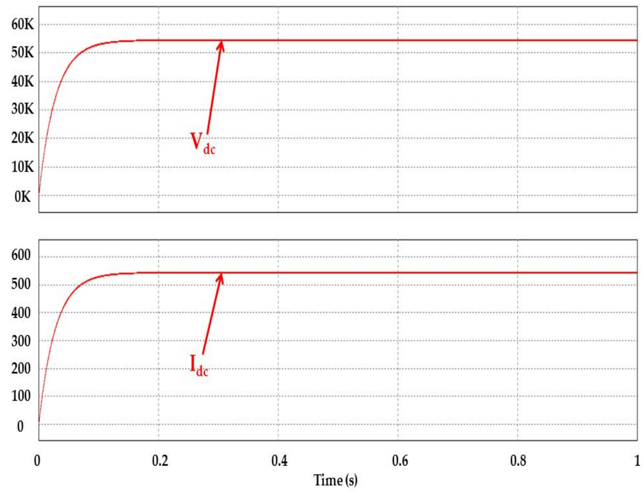

Fig. 5: DC link voltage and current waveforms for open loop system

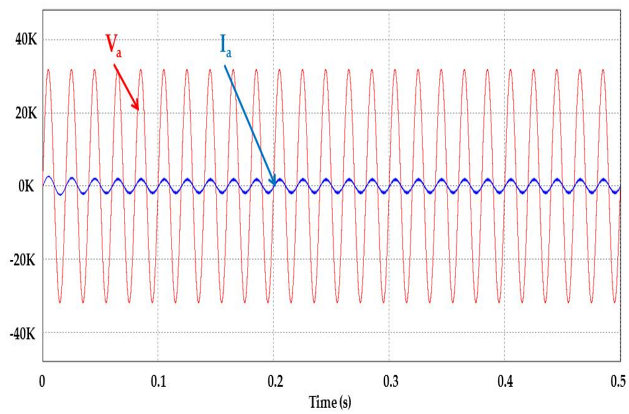

Fig. 6: Input voltage and current waveforms for open loop system which are in-phase

6. Simulation and Results for Closed Loop System

Fig. 7 gives the block diagram of the closed loop circuit that has been implemented. Here, the output DC voltage is sensed and compared with a reference voltage and through a PI regulator, the error signal generated is fed back to the input and accordingly the gating signals to the IGBTs are modified in order to provide a constant DC voltage on the link. This type of control is called DC Voltage Balance Control.

Static Loading Conditions. The same block diagram of fig. 7 has been implemented in simulation and the relevant DC output waveforms obtained under static loading conditions are as shown in fig. 8.

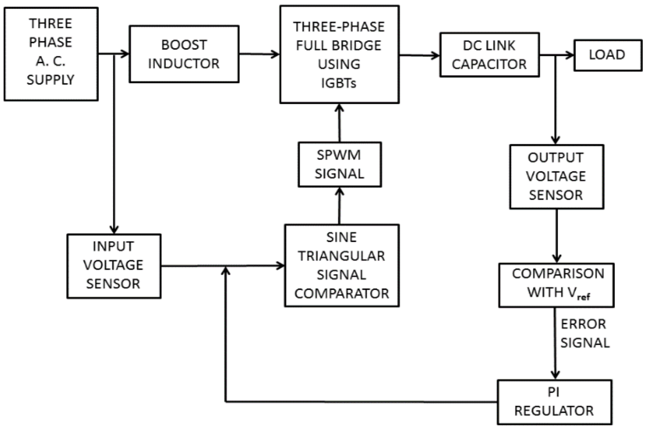

Fig. 7: Block diagram of the closed loop circuit.

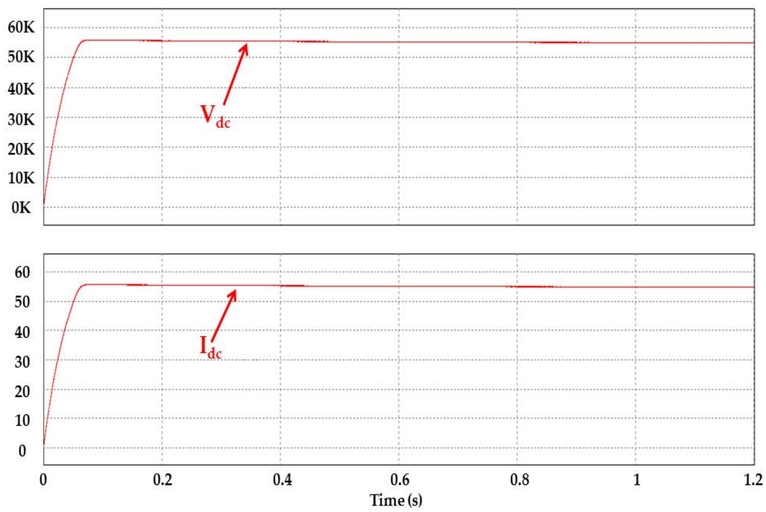

Fig. 8: DC link voltage and current waveforms for closed loop system under static loading condition

Dynamic Conditions with R Load Switching. Fig. 9 shows the waveforms of DC link voltage V_{dc} and input phase-A current I_a when R = 1000 Ω, and a resistor of 500 Ω is inserted at time t = 0.5 sec and a resistor of 250 Ω is inserted at time t = 0.7 sec and the loading is restored to 1000 Ω at t = 0.9 sec.

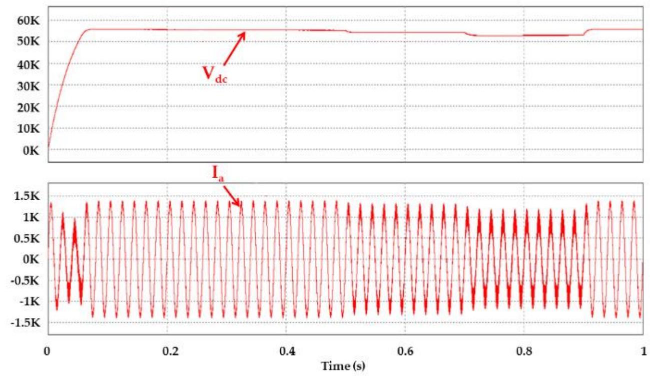

Fig. 9: V_{dc} and I_a for closed loop system under dynamic conditions with R load switching at t = 0.5 sec and t = 0.7 sec

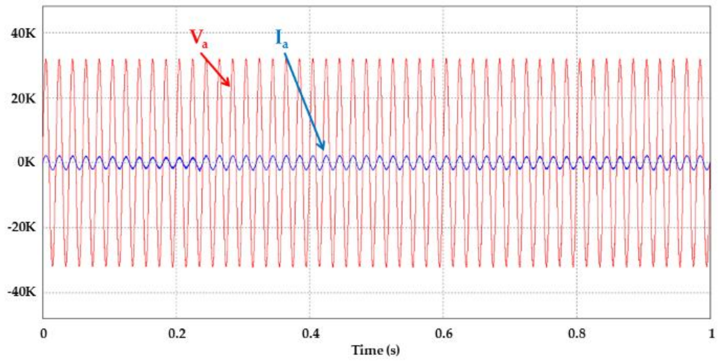

Fig. 10: Input voltage and current waveforms for closed loop system with R load showing unity power factor.

After the PI senses the changes in the loading, it tries to maintain the DC voltage to a constant value and accordingly, an offset equal to the error is introduced in the reference voltage and the output voltage after multiplying is given to the comparator. Fig. 10 shows the input voltage and current of phase-A which are in-phase, indicating a unity power factor operation with R load switching.

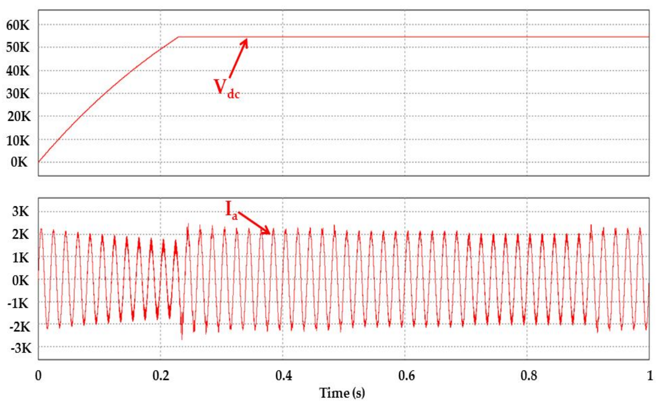

Fig. 11: Vdc and Ia for closed loop system with RL load switching at t = 0.5 sec and t = 0.7 sec

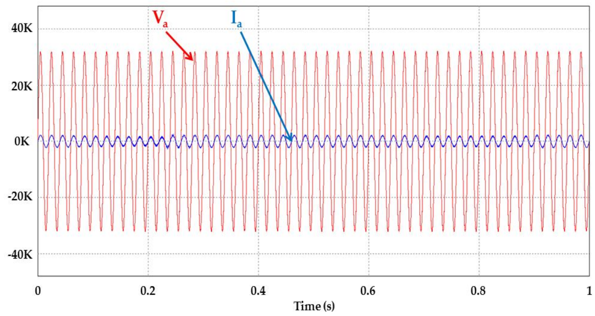

Fig. 12: Input voltage and current waveforms for closed loop system with RL load which are in-phase.

Dynamic Condition with RL Load Switching. Fig. 11 and 12 show the simulation results with a resistive load of 1000 Ω and an inductive load of 0.45 H and a load of R = 500 Ω, L = 0.225 H is inserted at t = 0.5 sec and R = 250 Ω, L = 0.1125 H at t = 0.7 sec. As the DC voltage is less than the reference voltage, with reduced value of load, the PI controller will command to increase the input gating signal for compensation of DC bus voltage drop.

7. Conclusion

This paper investigates the operation of three-phase pulse width modulated (PWM) boost rectifier topology operating as a voltage source converter (VSC). The converter under consideration is capable of: 1) voltage boost, 2) bidirectional power flow, and 3) unity power factor operation with nearly sinusoidal AC current at the input. The PWM rectifier is simulated and gives appropriate results under steady state as well as dynamic conditions with R load and RL load. Both the open loop as well as closed loop simulations have been carried out and a unity power factor as well as boost operation are successfully achieved.

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