Three phase PWM rectifier with open and short circuit switch fault analysis in railway traction

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Abstract— in this paper we propose a three phase PWM rectifier used for railway electrical traction drive system. The analysis on the rectifier is done with open and short circuit switch fault and observes the effect on the traction system.The design and analysis is carried out in MATLAB Simulink software with all possible graphical representation with both the cases (open switch fault and short circuit fault). Detection control structure and protection is provided with feedback loop control system protecting the railway traction system.

I. INTRODUCTION

The single-phase voltage source half-bridge inverters, are meant for lower voltage applications and are commonly used in power supplies.[8] Figure 1 shows the circuit schematic of this inverter.Low-order current harmonics get injected back to the source voltage by the operation of the inverter. This means that two large capacitors are needed for filtering purposes in this design.[8] As Figure 1 illustrates, only one switch can be on at time in each leg of the inverter. If both switches in a leg were on at the same time, the DC source will be shorted out.

Inverters can use several modulation techniques to control their switching schemes. The carrier-based PWM technique compares the AC output waveform, v_c, to a carrier voltage signal, v_Δ. When v_c is greater than v_Δ, S+ is on, and when v_c is less than v_Δ, S- is on. When the AC output is at frequency fc with its amplitude at v_c, and the triangular carrier signal is at frequency f_Δ with its amplitude at v_Δ, the PWM becomes a special sinusoidal case of the carrier based PWM.[8] This case is dubbed sinusoidal pulse-width modulation (SPWM).For this, the modulation index, or amplitude-modulation ratio, is defined as$m_a = v_c / v_\Delta$.

The normalized carrier frequency, or frequency-modulation ratio, is calculated using the equation $m_f = f_\Delta / f_c$.

Using selective harmonic elimination (SHE) as a modulation technique allows the switching of the inverter to selectively eliminate intrinsic harmonics. The fundamental component of the AC output voltage can also be adjusted within a desirable range. Since the AC output voltage obtained from this modulation technique has odd half and odd quarter wave symmetry, even harmonics do not exist.[8] Any undesirable odd (N-1) intrinsic harmonics from the output waveform can be eliminated.

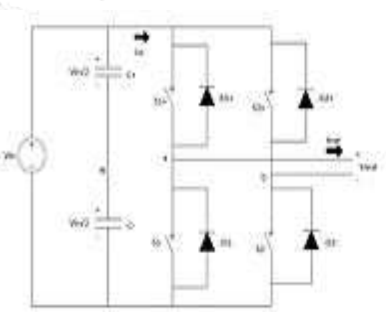

Fig. 1: Single phase inverter

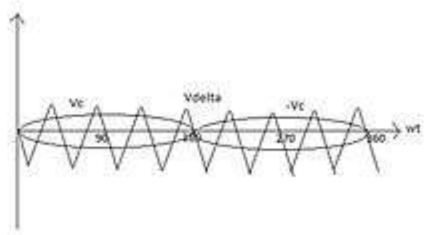

Fig. 2: PWM control for inverter or rectifier

The full-bridge inverter is similar to the half bridge-inverter, but it has an additional leg to connect the neutral point to the load.[8] Figure 2 shows the circuit schematic of the single-phase voltage source full-bridge inverter.

To avoid shorting out the voltage source, S1+ and S1- cannot be on at the same time, and S2+ and S2- also cannot be on at the same time. Any modulating technique used for the full-bridge configuration should have either the top or the bottom switch of each leg on at any given time. Due to the extra leg, the maximum amplitude of the output waveform is Vi, and is twice as large as the maximum achievable output amplitude for the half-bridge configuration.[8]

As was the case for the half-bridge SHE, the AC output voltage contains no even harmonics due to its odd half and odd quarter wave symmetry.

Surveys regarding open-switch fault diagnosis methods for the three-phase PWM inverters have been reported in [5] and [6]. However, open-switch fault diagnosis method related to the single-phase PWM rectifier is rarely found. In [27], the operation of the single-phase PWM rectifier under faulty conditions has been investigated and an open-switch fault detection method which analyzes the average value of the catenary current has been presented. However, this method can only detect the faulty IGBT switch pairs T1T4 or T2T3 in the single-phase PWM rectifier circuit as shown in Fig. 3, whereas the faulty switch cannot be located. A continuous condition monitor method for single-phase H-bridge converters by adding an additional current sensor was suggested in [8]. A fault detection and fault tolerant control method based on a state observer for the sensors in a single-phase rectifier has been proposed in [9].

The fault frequency of power modules in the grid-side rectifier is higher than that of the motor-side inverter, due to the more complicated operating condition and higher harmonic components [30], [31]. It will be shown that owing to the constant frequency control strategy and smaller power fluctuations, the model-based method is quite suitable for single-phase PWM rectifiers. It will be shown that this proposed method cannot only detect a faulty rectifier, but can also locate the faulty switch without any additional hardware. Only the values of the catenary current, the dc-link voltage and the command signals from the TCU are needed to create the MLD model.

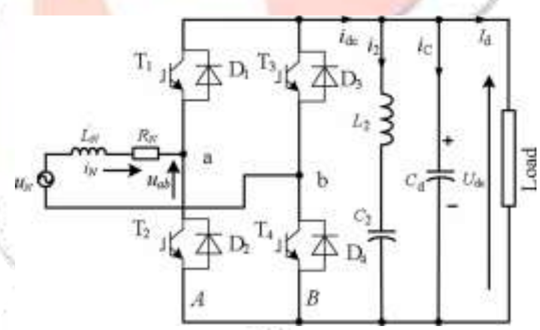

Fig. 3: Single phase controlled rectifier

II. CONTROL PWM TECHNIQUE

The pulse width modulation technique is generally used for the conversion of DC to AC waveforms. A full bridge inverter with six IGBTs can be used to convert DC to three phase AC. Each phase has to be phase shifted to each other by 120^0 and has to be in synchronization with the grid to which it is being connected. The pulses are to be given to the IGBTs are generated with a reference or fundamental waveform compared with a triangular waveform.

The fundamental waveform has the frequency of the grid and the triangular or carrier waveform has higher frequency to create a modulation signal. The diagram of the fundamental and the carrier waveform are shown below in fig. 4. Six pulses are formed by applying NOT gates to the three pulses produced by the comparison of the fundamental and carrier waveforms. The generated pulses are fed to the VSI (Voltage source Inverter) with G1 G2 G3 G4 G5 and G6 switches. A simple construction of VSI is shown in fig. 1

The rating of IGBT is taken as

Internal resistance Ron = 0.001 ohms

Snubber resistance Rs = 100 kohms

Snubber capacitance Cs = 1F

Due to the impedance load the load current gets ceased during sudden switch OFF of the IGBT switch and generate high voltage peaks in the output voltage. To avoid this an anti parallel diode is attached to the switch (IGBT) so that the inductor current from the impedance load can pass through the diode.

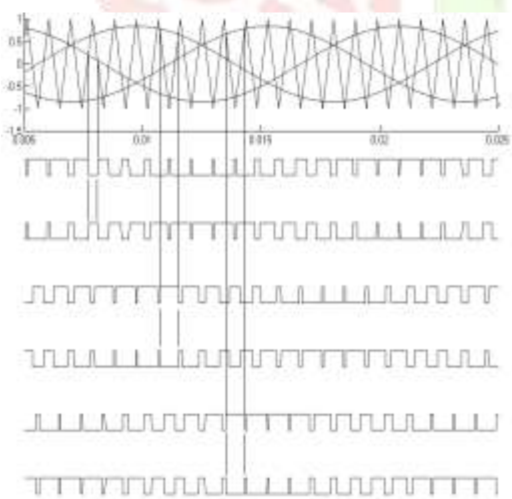

Fig. 4: Generation of pulses with respect to reference fundamental waveforms

The higher the carrier frequency the lower the harmonics developed by the inverter. To eliminate the minimum harmonics we also use LC filter to filter the higher order harmonics from the three phase AC voltage waveforms. The three sinusoidal fundamental waveforms are generated as

Va= VmSin(wt)

Vb= VmSin(wt+2pi/3)

Vc= Vm Sin (wt-2pi/3)

Where Vm= maximum voltage ie., amplitude of sinusoidal waveform which is '1'

The modulation index in PWM waveform is controlled by controlling the amplitude of the fundamental waveform. By reducing amplitude of the sinusoidal wave the space between the pulse is increased reducing the amplitude of the PWM waveform. The phase of the reference wave considered decides the phase of the PWM waveform.

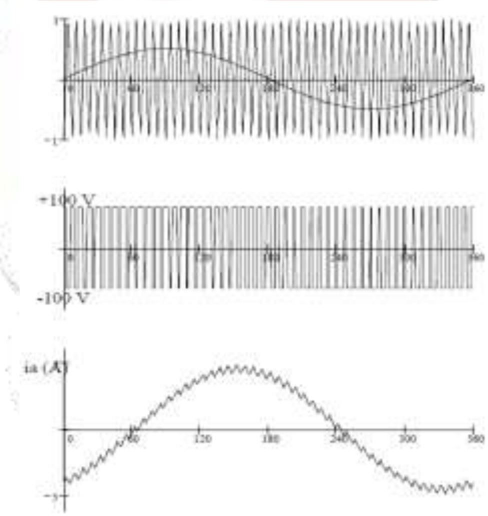

Fig. 5: Effect of change in amplitude of sinusoidal waveform

III. FAULT ANALYSIS

In order to clearly analyze the IGBT open-switch fault conditions in the single-phase PWM rectifier, it is assumed that the upper switch of leg A is an open-circuit faulty switch, T1.Itis assumed that the catenary current's reference direction is from the traction winding to the rectifier. As shown in Fig. 1, the current could flow through the bypass diode D1 associated with the faulty switch when the catenary current is positive. Thus, there is no change in the catenary current waveform during the first half current cycle after the open-switch fault occurs. However, when the catenary current is negative, current cannot flow through the bypass diode D1. If the catenary current is negative, the rectifier cannot operate normally when the command signals are (1010), (1001), and (1000).

Beginning with the command signal (1010), the upper switch of leg A is turned on when the switch T1 is in the normal condition. The catenary current flows through the bypass diode,D3, and switch, T1, shown as Fig. 3 In this context, the grid voltage charges the inductor to facilitate energy storage, and the amplitude of the catenary current is increasing. Meanwhile, the energy stored in the dc-link capacitor is released to the load. Thus, the dc-link voltage is reducing.However, if switch T1 in leg A is open circuited due to a fault condition while its firing signal is high, the energy stored in the inductor is released. Since the current flowing through an inductor cannot change instantaneously, it must flow through the bypass diode D2 and D3, shown as Fig. 3. In this condition, the grid voltage and the inductor charge the dc-link capacitor simultaneously. Thus, the amplitude of the catenary current is declining and the dc-link voltage is increasing. But, due to the reducing of the catenary current amplitude, the increasing amplitude of dc-link voltage is limited, and depends on the load.

When the command is (1001), switch T1 in leg A and switch T4 in leg B are turned on when T1 not faulted, shown as Fig. 3.In this case, both the grid voltage and the dc-link voltage charge the inductor, resulting in energy storage. Therefore, the amplitude of the catenary current increases sharply, and the dc-link voltage is reducing.But due to the open-circuit fault of switch T1, the catenary current can only flow through the bypass diode D2 and switchT4, shown as Fig. 3. In this case, only the grid voltage charges the inductor. Thus, the increasing amplitude of catenary current is less than those in normal mode. Also, the energy stored in the dc-link capacitor is released to the load. So, the dc-link voltage is reducing.

With the command (1000), both the fault and the normal mode are the same as command (1010). Since the signal (1000) is effective only when the switch operates during the dead-time, this command signal has little effect on the rectifier when there is an open-circuit fault in T1.Therefore, the amplitudes of the catenary current and the dc-link voltage both are declining due to an open-circuit fault in T1, shown as Fig. 4. All the previous explanations can be extended to the remaining switches, T2,T3, and T4.

B. Diode Open-Circuit Fault Analysis

As for diode open-circuit fault, it is also assumed that the upper diode of leg A is an open-circuit faulty diode, D1.As shown in Fig. 1, the catenary current flows through the switch, T1, or the clamping diode, D2, when the current is negative.

The clamping diode D1 does not work during this half period of catenary current. Thus, there is no change in the catenary current waveform when the current is negative after the diode D1 occurring open-circuit fault. However, when the catenary current is positive, current has no way to flow through unless the switch T2 is turned on, shown as Fig. 4. Since the current flowing through an inductor cannot change instantaneously, this abrupt mutation may result in a sharp increase of the inductor voltage. According to the Kirchhoff's law, the input voltage of the rectifier rises abruptly, which may lead to a tremendous voltage stress on the switches of leg A, T1 and T2.Asshownin the Fig. 3, the input voltage could be 50 000 V in the brief moment when the catenary current is open. The rated blocking voltage of the IGBT is 6.5 kV. Therefore, the abnormal voltage stress caused by the diode open-circuit fault is much higher than the blocking voltage of the IGBT, which may result in the IG

BTs overvoltage failure in a short time.[2] and[3] mentioned that the reason of the IGBT overvoltage breakdown failure is due to the thermal stresses and heat accumulations in the junction, which may result in an IGBT short circuit during a short transient. Thus, diode open-circuit fault is one of the most damaging failures in the traction converter. Moreover, hardware-based protection schemes are employed in control circuits of the IGBTs to prevent the abnormal overcurrent and overvolt-age issues. Therefore, this paper focuses on the open-switch fault diagnosis method for IGBTs of the single-phase PWM rectifier.

IV. RESULTS AND OUTPUTS

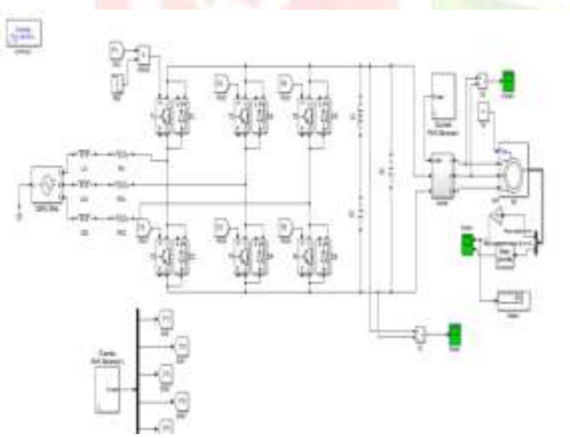

Fig. 6: MATLAB modeling of the three phase controlled rectifier

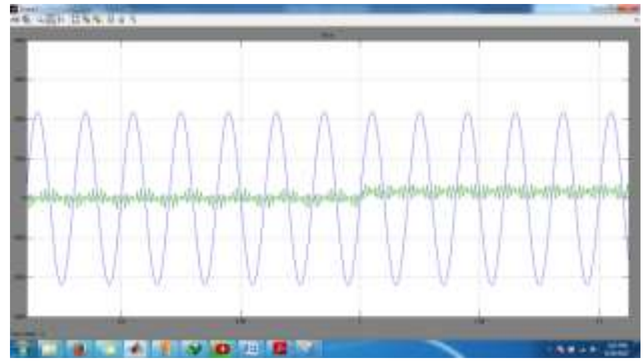

Fig.7 : Input voltage and current

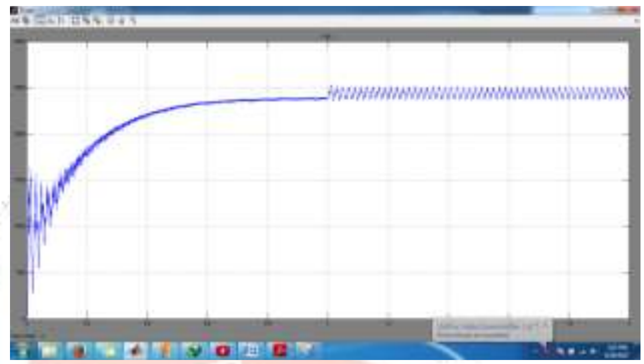

Fig. 8: DC voltage after rectification

Fig. 9: PWM voltage

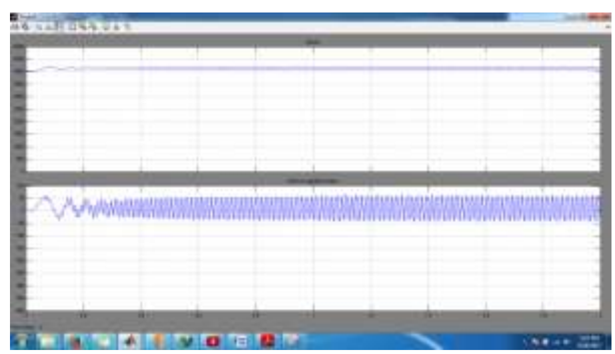

Fig. 10: Induction motor characteristics

V. CONCLUSION

The rectifier connected to the single phase source controls the DC voltage and in turn control the output voltage of the inverter. The change in the DC voltage of the rectifier changes the speed of the induction motor connected to inverter. The active switches are tested with open circuit fault and the DC voltage is maintained with amplitude running the induction motor in even faulty condition.

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