A Fuzzy Logic Fault Ride-Through Scheme for Electric Vehicles Using PMSM -AC Drives

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Abstract: The paper validated a new Compensating device for Fault Ride Through (FRT) the permanent magnet synchronous motors (PMSM) driving AC Drives used in Electric Vehicle. The electric vehicle utilizes two PMSMs to drive the two front wheels. The battery source is regulated and controlled by a boost type dc-dc converter. The new FRT compensating device is interfaced to the VSI-inverter feeding the PMSM drive motors. Type 2- Fuzzy Logic Controller (T2FLC) is utilized in the regulation of the output voltage of the boost dc-dc converter. The unified drive dc-ac scheme is simulated using the Matlab/Simulink software environment. Dynamic simulation of short circuit fault conditions at different parts of the unified drive system. The stator current, the rotor speed, and the electric torque for each PMSM are compared for both short and open circuit faults without and with the compensating device. Digital simulation results validated the effectiveness and fast damping with fast fault-recovery time and supply continuity during short circuit and open circuit faults.

Keywords: Fault Ride Through, PMSM-Drives, Electric Vehicles, Type2-Fuzzy Logic Control, Compensating Device

1. Introduction

The exhaust gaseous emissions from fossil-fuel-internal combustion engine (ICE) vehicles are the major source of urban smog and environmental pollution. Electrical vehicle (EV) produces no exhaust and is low noise. There is also an additional economic factor in converting to EVs as the ICE engine efficiency is inherently low [1]. EV attracted the attention of many car industries for many decades. However, EV has some drawbacks, such as short driving distance, long recharging time and high costs. The EV power source is the dc battery which acts as a limited charge "gas tank" and supplies the electric motor drive with the energy necessary to move the vehicle. When battery is depleted, the batteries are recharged using the electric grid, either from a wall socket or a dedicated charging station. The DC voltage from the battery pack is converted into the AC three-phase voltage using VSI-inverter interface for dc-ac conversion.

One of the most common faults that may occur in EVs is the shortage of dc/ac supply due to faults in the batteries, inverter circuit, or controller, which may lead to hazardous problems during driving and/or acceleration or deceleration. To avoid these problems a new compensating device comprising low cost dc polarized capacitors, a two-pulse diode bridge, and a solid state MOSFET/IGBT, is proposed to control the dc supply and consequently the inverter supplying the PMSM driving the wheels. In the proposed design, two PMSMs are driving the car wheels, one for the left wheels and the second PMSM drives the right wheels. The new compensating PWM-switched circuit ensures the continuity of dc/ac supply to the two motor drives during acceleration as well as in cases of short circuit or open circuit in the supply side. T2FLC is designed and applied to control the switches of the compensating circuit and boost converter during normal operation or fault conditions.

In this paper, the unified drive system composed of the two PMSM drives, VSI-inverter, dc battery bank, dc supply, and the compensating circuit is modeled, [2]. Simulation results are presented for the cases of:

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- Normal operation while the vehicle is turning around a corner without compensating device,
- Normal operation while the vehicle is turning around a corner with the compensating circuit
- Operation with short circuited supply with and without the compensating circuit
- Operation with open circuited supply with and without the compensating circuit

Simulation results proved the effectiveness of the proposed circuit for FRT in EVs.

2. EV with new compensating circuit

Figure (1) shows the proposed system where each two wheels are operated by a PMSM. The compensating circuit is placed parallel to boost converter. In this design the electrical source is a battery bank, a boost converter, and inverter feeding the PMSM. The load consists of two PMSMs, one motor for left side wheel and the second motor for the right side wheel.

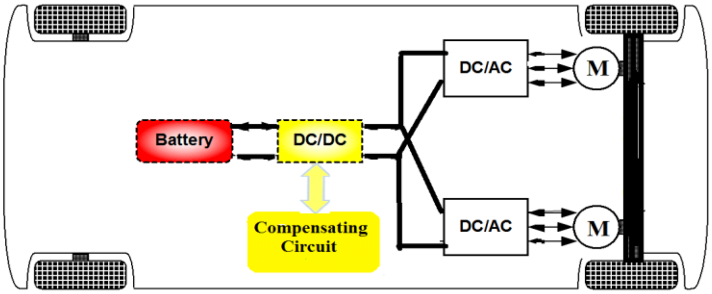


Figure 1. Block Diagram of the unified DC-AC Drive System.

3. System Modelling

A. Battery model

A basic electrical approach to a battery is shown in Figure 2 and Equation (1). It consists of a voltage source V_g and a resistor R_g. This generic model includes the main variables of the system, [3].

$$V_{bat} = V_g + IR_g \quad (1)$$

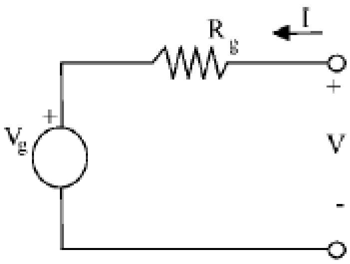


Figure 2. Equivalent circuit of the battery.

B. DC/DC converter with Type 2 Fuzzy Control

The boost converter is capable of producing a DC output voltage which is greater in magnitude than the DC input voltage. The arrangement for the boost converter is shown in figure 3, [4]. The output voltage of converter is done via T2FLC to follow the reference voltage.

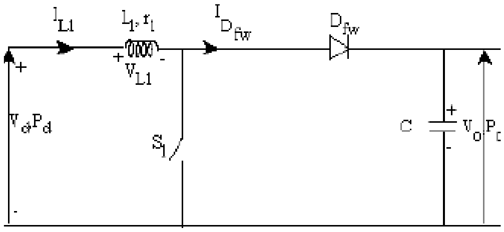


Figure 3. DC-DC boost converter (Chopper) circuit.

The major structure difference between type 1 and type 2 FLC is that the defuzzifier block of a type-1 FLC is replaced by the output processing block in a type-2 FLC which consists of type-reduction followed by defuzzification block as shown in figure 4., [5, 6]. T2FLC, can be used when the circumstances are uncertain to determine exact membership grades such as when the training data is affected by noise. T2FLC reaches steady state value faster than type-1 FLC, [7]. The simulink block diagram of this type is shown in figure 5, [8].

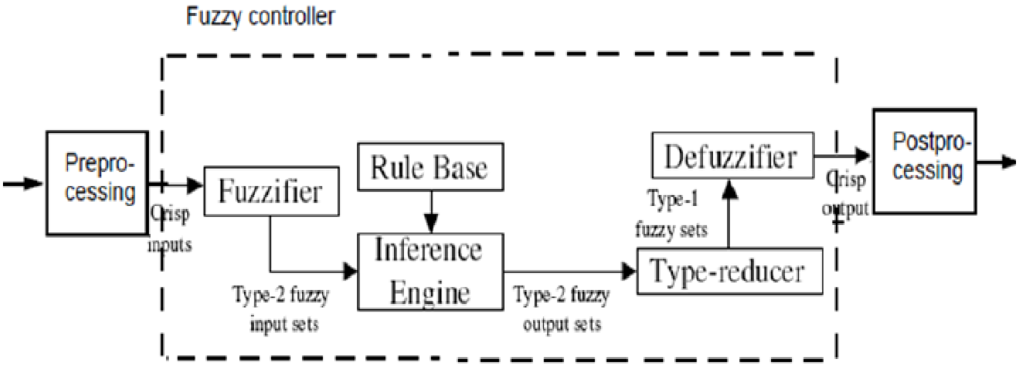


Figure 4. The block diagram of type-2 FLS.

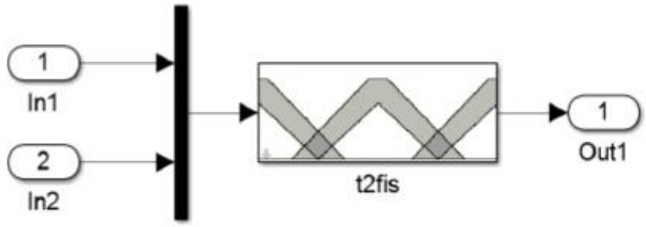


Figure 5. Matlab-simulink block diagram of type-2 FLS.

C. New Compensating circuit

Figure 6 shows the vehicle electrical system with compensating circuit. The circuit comprises three capacitors (C_f, C_{f1}, and C_s), two pulse diode rectifier-bridge, and a small smoothing reactor (L_f) with additional tuning resistor (R_f), [2]. The filter-compensator is used to stabilize the common interface DC bus, ensure efficient utilization and minimal inrush current conditions under different charging and fault conditions. If the first IGBT is switched on, the second IGBT is switched off. Controlling the on-off switching is done via T2FLC.

D. PMSM model

The model of PMSM is consists of the voltage equations are given by, [9-10]:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q$$
$$V_d = R_s i_d + \omega_r \lambda_q + \rho \lambda_d \qquad (2)$$

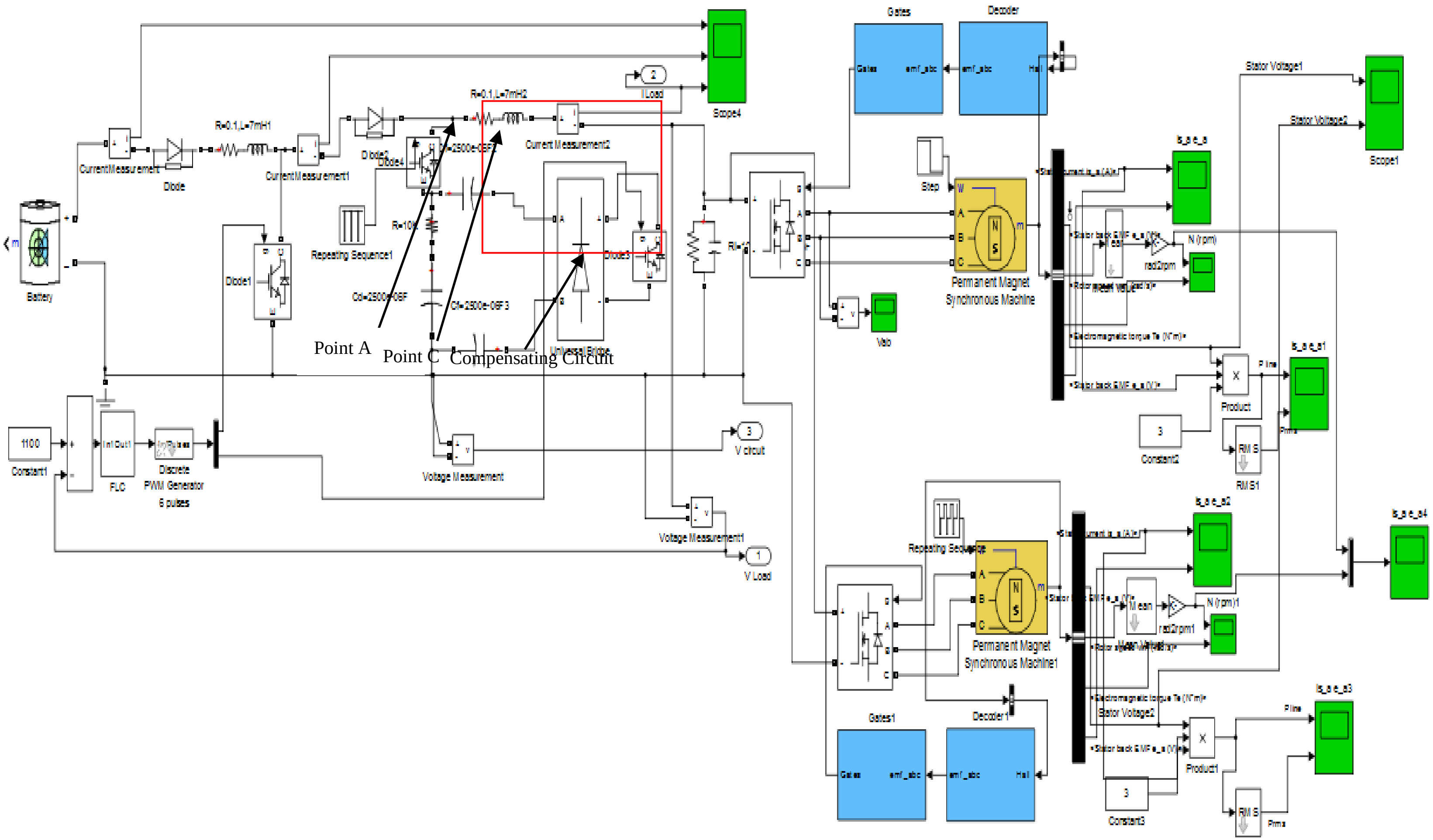


Figure 6. Unified DC-AC Drive System with Compensating Circuit.

And Flux Linkages are given by

$$\lambda_q = L_q i_q$$
$$\lambda_d = L_d i_d + \lambda_f \quad (3)$$

The developed torque motor is being given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q - \lambda_q i_d) \quad (4)$$

The mechanical Torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \quad (5)$$

4. Simulation and Discussion

The proposed battery-powered EV employing the compensating circuit is modeled and simulated with Matlab/Simulink, monitoring the voltage, current profiles, speed, and electric torque for both motor drives for the cases of normal operation while the vehicle is turning around a corner, with short circuit and open circuit supply faults. The results with and without the compensating circuit are presented.

A. Results for normal operation while turning around a corner

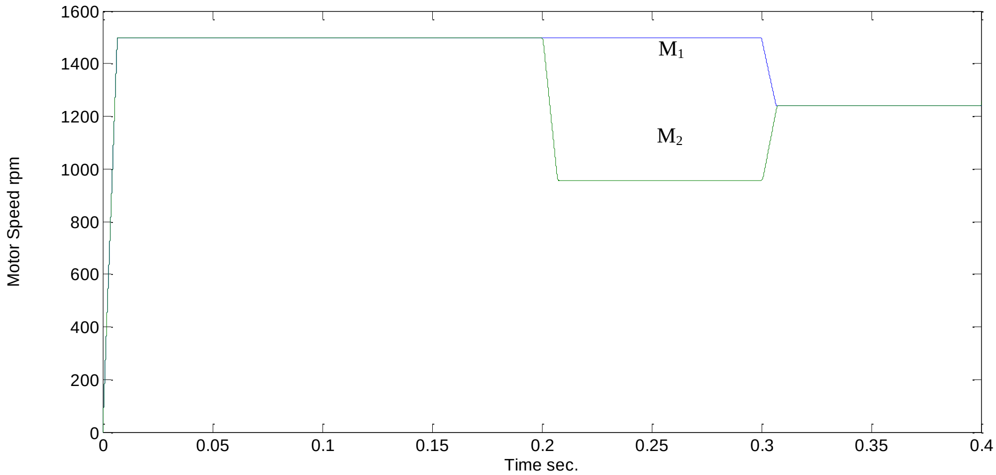
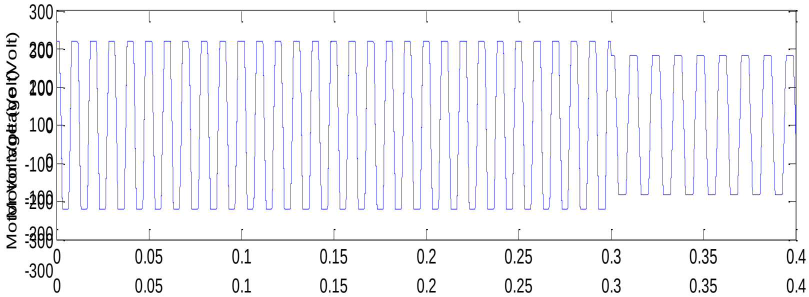
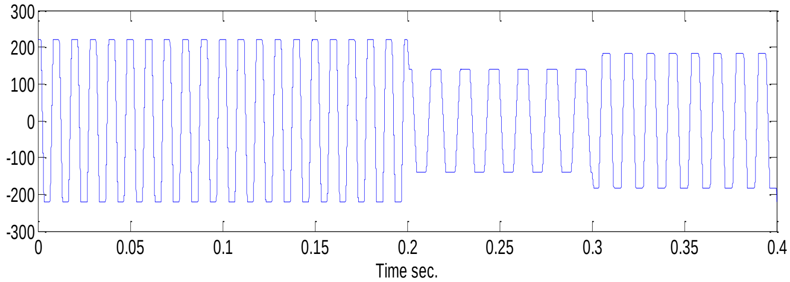


Figure 7. the speed motor for two motors

Figures 7 & 8 show the simulation results when the vehicle is turning around a corner. In Figure 7, the left-side wheels speed is lower than the right-side wheels' speed while turning, after which the two wheels speed are equal. In Figure 8, the corresponding stator voltages are shown. A T2FLC is applied to control the converter voltage which feeds the two inverters with motors to achieve the required vehicle motion. Figure 9 show the stator current for both motors, where the increase in the current of the left-side wheels' motor corresponds to the decrease in current of the right-side wheels' motor while the vehicle is turning around a corner.



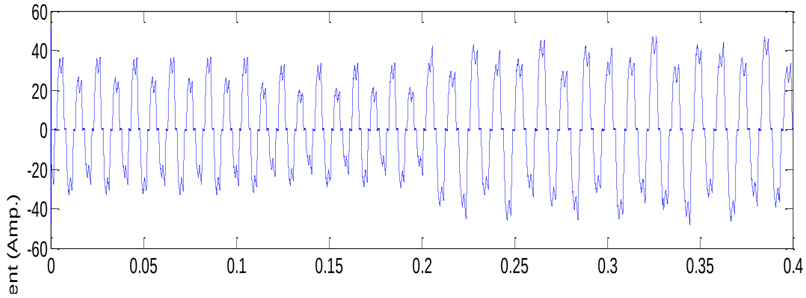
a. For M_1



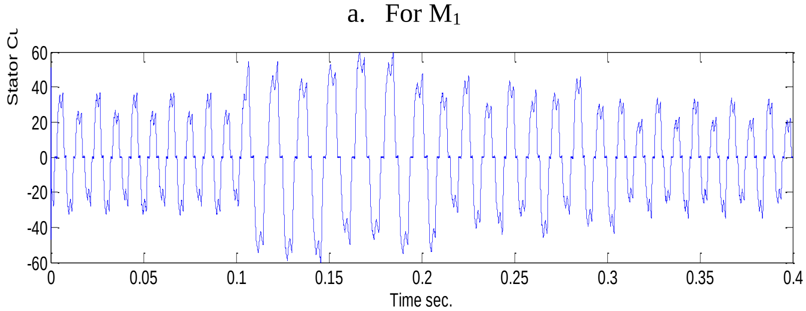
b. For M_2

Figure 8. The stator voltages of two motors.

B. Simulation Results for short circuit at point A before the compensating circuit



a. For M_1



b. For M_2

Figure 9. The stator current of two motors.

A supply short circuit fault is assumed for 0.02 seconds starting from 0.2 sec. Figure 10 shows the source current, the current before the compensating circuit, and the current at the load (input to inverter feeding the PMSM) connection point respectively. The effect of reducing the fault current peak as well as the fast recovery from the short circuit current at the load side is clear. It is noticed that a delay occurs between the moment of fault occurrence at the source and the fault effect at the load side. This delay is due to the compensating circuit inductance. Figure 11 demonstrates the stator current for the two motor. While, Figure 12 shows the electromagnetic torque for the right-side and left-side of wheels' motors.

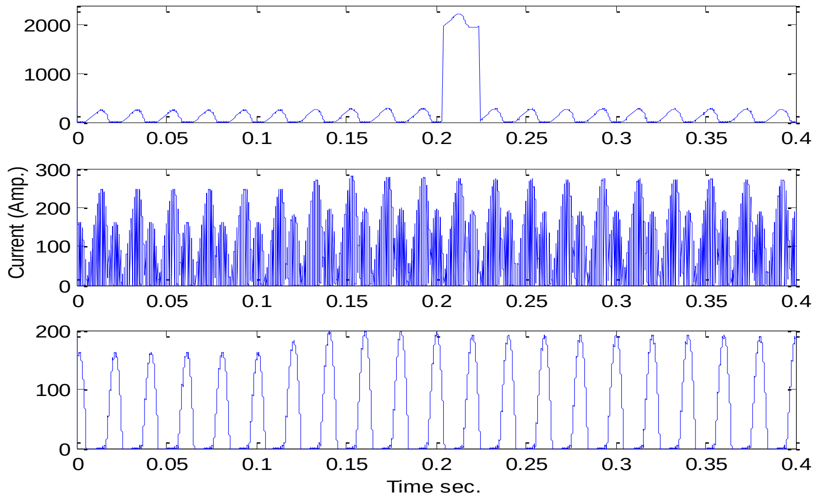
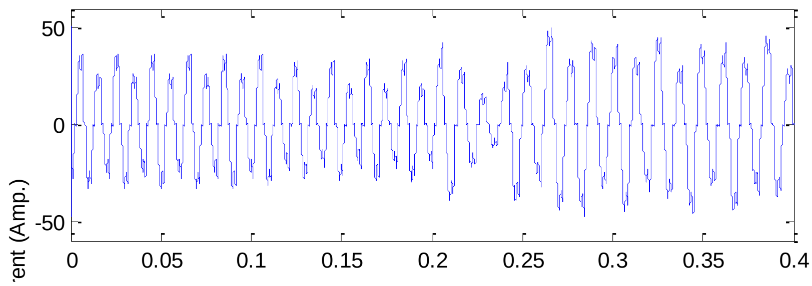
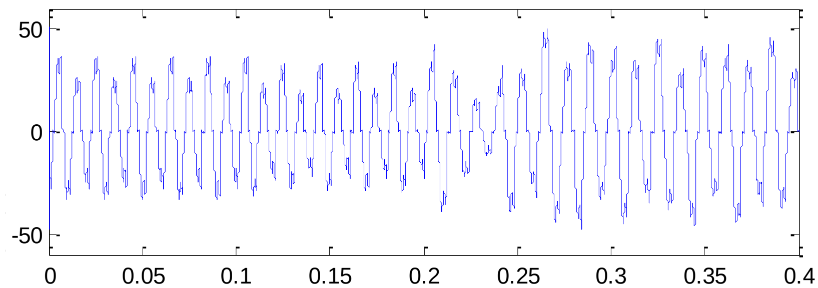


Figure 10. three point of current at source, before compensating circuit, and input to inverter feeding the PMSM.

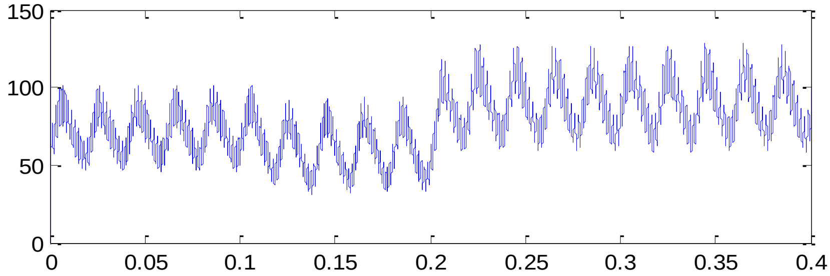


a. For M_1

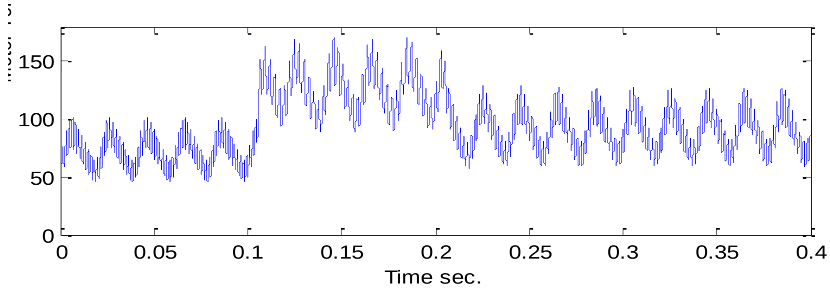


b. For M_2

Figure 11. The stator current for the two motor at short circuit source



a. For M_1



b. For M_2

Figure 12. The electromagnetic torque at short circuit source from 0.2 to 0.22 sec.

C. Results for short circuit at point C with the compensating circuit

A short circuit is taking place after compensating circuit. Figure 13 shows the current at the source, and at the inverter feeding the PMSM respectively. It is clear that the absence of the compensating circuit led to large increase in the short circuit current at the 3 considered points. The increase in current continues which may lead to damage the EV circuits and components. Such behavior proves the importance of adding the proposed compensating circuit to the source feeding the EV.

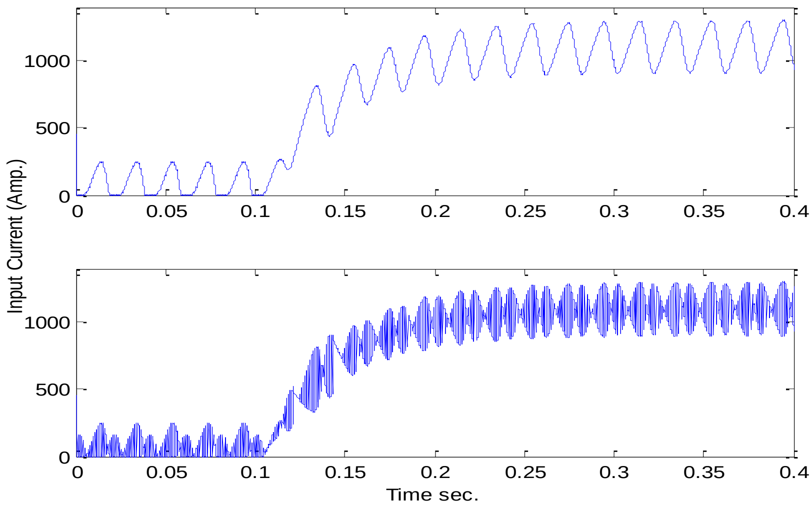


Figure 13, Source Current, and the input to inverter feeding the PMSM when short circuit after compensating circuit.

D. Simulation Results for Open-circuit supply

Figure 14 plots the supply current, the current at the input terminal of the proposed compensating circuit, and the input to inverter feeding the PMSM current respectively when assuming a 0.05 seconds-duration open circuit fault starting from 0.2 second. The load current is not pure zero but contains few humps due to the capacitors of the compensating circuit, which lead to the continuity in the motor operation as shown from the stator emf for both motors.

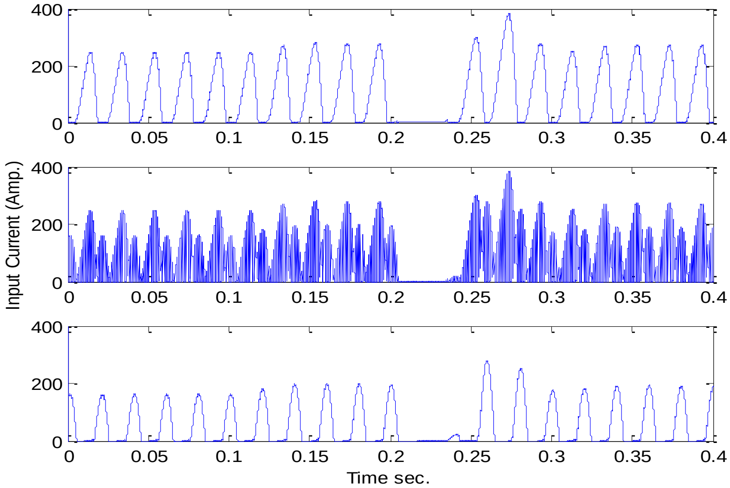
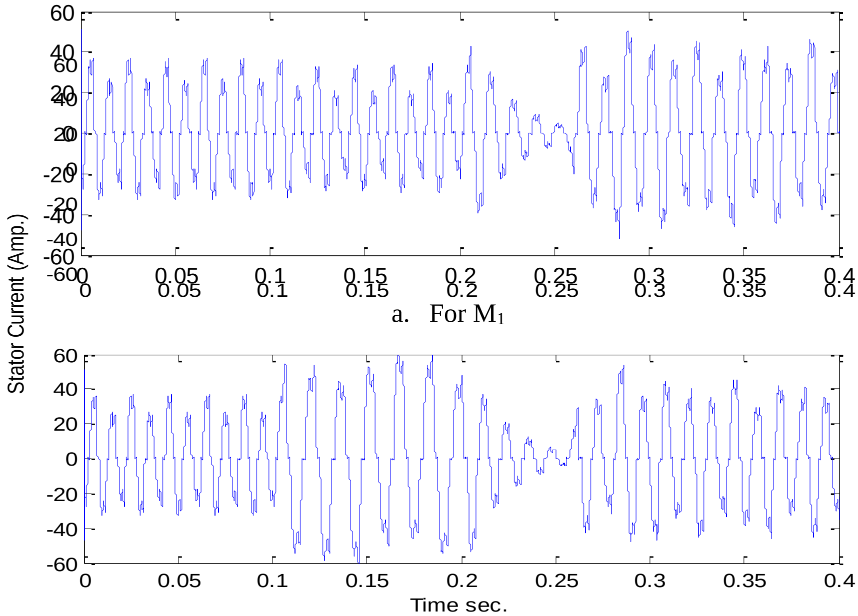


Figure 14. Supply current, the current at the input terminal of compensating circuit, and the input to inverter feeding the PMSM current, respectively.

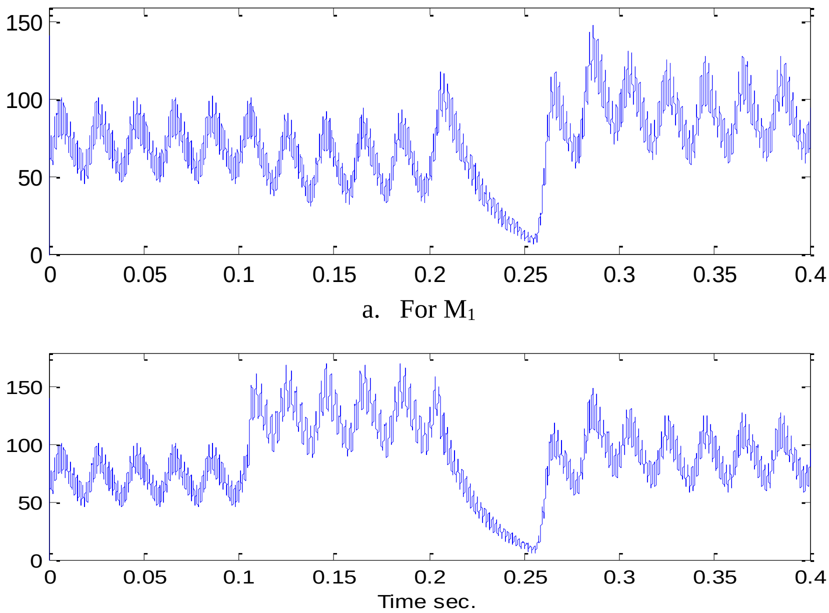
However continuity of vehicle motion after an open circuit supply is for very short time (about 0.01 seconds). This sort time is essential for preventing sudden stop, which may have danger consequences. Figures 15 and 16 show the stator current, and electric torque for the two motors during open circuit, respectively.



a. For M_1

b. For M_2

Figure 15. The stator current for two motors during open circuit.



b. For M_2

Figure 16. The electric torque for two motors during open circuit.

5. Conclusion

The paper validated a new compensating device for FRT in AC drives an electric vehicle driven by two PMSMs. A battery bank followed by a DC-DC boost converter and two VSI-inverters driving the two-wheel PMSMs of the EV drive. The new compensating circuit is designed to stabilize the common DC bus voltage, reduce inrush currents, eliminate voltage transients and mitigate FRT conditions introduced by short circuit and open circuit faults on the EV. It is also used to smooth the DC output of the DC-DC boost converter during normal operation and reduce motor torque and current transients. The EV circuit is simulated without and with the new compensating device circuit. T2FLC is designed to control the DC-DC converter and the compensating circuit switches to stable operation during short circuit faults and continuity of motion after open circuit faults. Comparing results with and without the proposed circuit proved its effectiveness for FRT. The same circuit is being tested for microgrid PV-Battery-Fuel Cell DC-AC interface for voltage stabilization on DC side and reduced harmonics in the AC interface to electric grid.

Appendix

1- PMSM parameter

P=25 KW, 4 poles, V =220 V Trapezoidal, R_s = 2.875 Ω, L_s = 8.5 mH

2- New Compensating Circuit

C_f = C_s = 2500 μF, R_d = 10 KΩ, R_f = 0.1 Ω , L_f= 7mH.

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