Fault Tolerant Power Conversion System With Interleaved Hybridized Energy Storage Systems for a PMSM Traction Motor Drive in Electrified Powertrain

by

Varun Harvey Vinod Fnu

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Engineering
(Automotive Systems Engineering)
in the University of Michigan – Dearborn
2020

Master's Thesis Committee:

Associate Professor Taehyung Kim, Chair
Professor Hong Tae Kang
Associate Professor Sang Hwan Kim

Acknowledgements

I would like to acknowledge my faculty advisor Prof. Taehyung Kim for his supreme guidance through each phase of this project and for inspiring me towards the development of innovative technologies, would also like to thank him for all the support and encouragement I have received from him during the course of my Master's Degree. The knowledge and experience I have gained from him during the time of me working under him will stay with me for a very long time. I would also like to thank him for his constant motivation, enthusiasm and patience, it was a wonderful experience working under him and constantly gaining and learning from the way he works. My sincere gratitude to Prof. Sang-Hwan Kim and Prof. Hong Tae Kang for all of their interest and support towards my research topic. Finally, my sincere thanks to Prof. Taehyun Shim, Director of Automotive Systems Engineering at the University of Michigan Dearborn for providing me with this wonderful opportunity of pursuing my Masters in ASE in this prestigious university and hence providing me with this opportunity of pursuing thesis.

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Abstract

The dissertation presents a fault tolerant power conversion system that are most commonly used in interleaved hybridized energy storage systems for PMSM traction motor drive applications in electrified powertrains. The methodology developed has the capability to detect switching faults induced in power conversion systems, on detection it has the capability to isolate the fault and also offers a rectification strategy for rectifying the switching fault to ensure continuous and reliable operation of the electrified powertrain in case of a switching failure. Fast running physics based model of a PMSM motor drive with field-oriented control was developed, fast running model of the interleaved bi-Directional DC-DC converter was also developed, the two models were then integrated to simulate switch-fault failures. The concept of the methodology developed involves replacing the faulted phase/leg of the motor drive in case of a switching failure by the additional leg on the interleaved bi-directional DC-DC converter, to ensure in case of a switch-failure other electrical components on the drive-train are safe-guarded and to also ensure the vehicle is able to operate normally which would not be the case otherwise.

All the models and simulations were developed and performed respectively on PSIM and the results are compared and discussed to verify the proposed methodology.

Chapter 1: Introduction

Efficient consumption of energy along with sustainable energy is one of the biggest concerns in the automotive industry, industry, as the norms for emissions set by EPA get more stringent, majority of the automotive manufacturers are shifting their focus towards electrified powertrains**.** These systems tend to offer a significant increase in the overall efficiency of the Propulsion System.

Electrified Propulsion Systems can be designed to satisfy multiple objective functions such as increase in fuel economy, increase in performance, increase in efficiency, better drivability and NVH. The reasons for the above mentioned advantages are Engine Start-Stop feature, that enables the engine to be shut-off during coast down or idle. Ability to operate the engine at the point of highest efficiency in Series Hybrid which results in increase of fuel economy. Instant torque at the wheels because of electric motors giving better performance.

Electrified Powertrains typically consist of an engine, transmission, multiple clutches, electric motor, battery pack and power electronics. Power electronics are essentially developed for control along with conversion of electrical power from one form to another with the application of electrical and electronics engineering. The conversion of electrical power is achieved using switching devices such as diode, MOSFET, thyristor, IGBT. Power conversion from one form to another is done in the following four ways:

- AC-AC (Converter)
- DC-DC (Converter)

- AC-DC (Rectifier)
- DC-AC (Inverter)

Application of these converters would be:

- DC-DC Converter are used to step-up battery voltage to DC-link or required bus voltage, they can also be used to step-down the bus voltage to the required battery voltage.
- AC-DC Converters are mainly used to convert motor regenerative alternating current to direct current required to charge the battery.
- DC-AC Converters (Inverters) are mainly used to convert battery direct current to alternating current required by the motor to drive the vehicle.
- AC-AC Converters are mainly used to increase or decrease the frequency of the sinusoidal alternating current from input to output, mainly used for variable speed applications.

Most commonly used electrical motors for automotive applications are:

- Brushless DC Motor
- Permanent Magnet Synchronous Motor
- Three phase Induction Motors
- Switch Reluctance Motor

In this project, Permanent Magnet Synchronous Motor has been chosen mainly because of higher efficiency, lower rotor inertia, less noisy, higher torque output and hence better performance, more reliable and they have relatively lower torque ripple, efficient heat dissipation.

1.1 Field Oriented Control

Field Oriented Control of PMSM motor drive essentially implements a field oriented control strategy, the control strategy decouples torque and flux by transforming stationery phase to currents to rotating frame of reference. For vector control, this is one of the most efficient strategies available. The control strategy essentially transforms the three phase current waveforms that are a function of speed and time to being a function independent of time and into a two-dimensional co-ordinate system, the co-ordinates being d and q**,** the co-ordinate system has a rotating frame of reference [1]. Field Oriented Control functions based on projections of all current waveforms on to d and q axes and hence this leads to an accurate prediction in both steady and transient states.

1.2 FOC Control Logic Flow

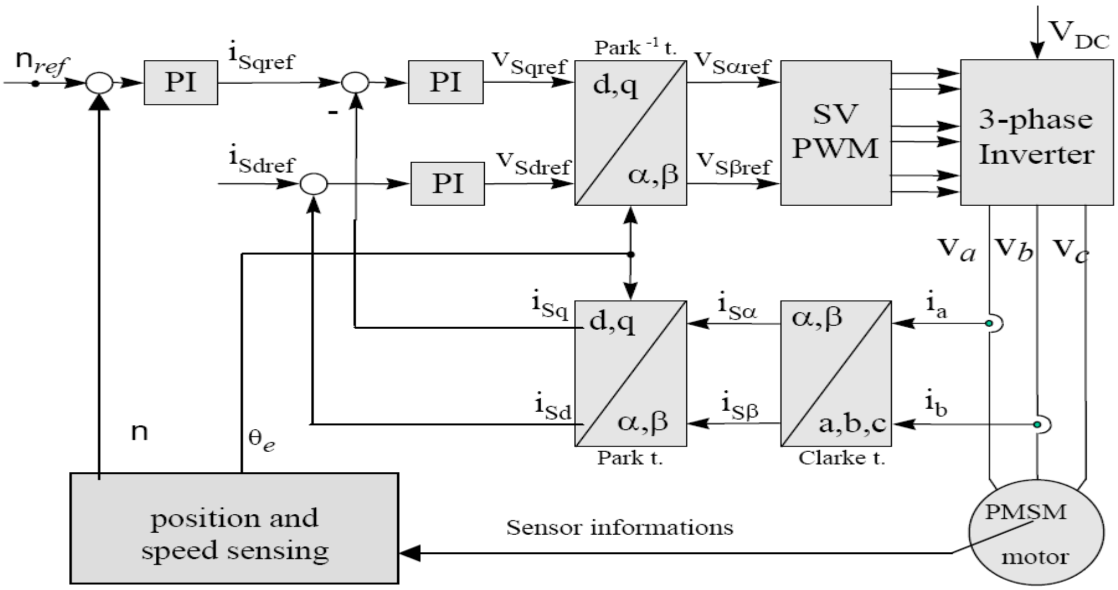


Figure 1: FOC logic flow [1]

As seen from Figure 1, the logic requires two inputs that are to be fed into the system, them being the torque component of the stator current and the flux component of stator current. The torque component hence aligns with the q-axis whereas the flux component is found to align with the d-axis. In order to incorporate Clark’s transform which is explained in detail in the following sections, the two most important parameter are measurements of the two phase currents Ia, Ib, the outputs of the Clark’s transformation block being current vectors along α-axis and β-axis as shown in figure 1 as Isα and Isβ [1].

The outputs of Clarke’s transforms are fed in as inputs to Park’s transform that output stator current components along the d-axis and q-axis [1]. The actual values obtained Isd & Isq are then compared with the commanded values of Isd_ref and Isq_ref as shown in figure 1, the flux component of the stator current is Isd_ref and the torque component of the stator current is Isq_ref [1].

Motor Position in terms of reference position and Motor Speed are continuously calculated and monitored through real sensors on the vehicle and are fed into this model. Motor Speed measured by the sensor is compared against the reference/requested speed of the motor [1]. The difference in speed acts as an error and feeds into the PI controller which then outputs Isq_ref which is the torque component of the stator current, as additional torque needs to be produced in the case actual speed is less than desired speed and hence the vehicle has to accelerate, the PI controllers are tuned to ensure appropriate conversion of difference in speed to the desired Isq_ref values [1]. As the rotor flux is fixed for steady-state operation Isd_ref is zero.

The second PI controller is basically tuned to convert Isq_ref and Isd_ref to desired stator voltages along the d and q axes. These voltage signals are then fed into inverse Park Transformation Module, the following control module outputs reference voltage along the α and β reference frame. The obtained values of Vsα_ref and Vsβ_ref are then fed as input into the final control module called the Space Vector Pulse Width Modulation. The following control module outputs switching signals to all the switches of the 3-phase inverter [1].

1.3 Clarke Transformation

Clarke Transformation is a mathematical transformation tool that is employed to simplify the analysis of three-phase circuits. In this case it is about projecting current waveforms along a, b & c axes onto the α and β axes [1].

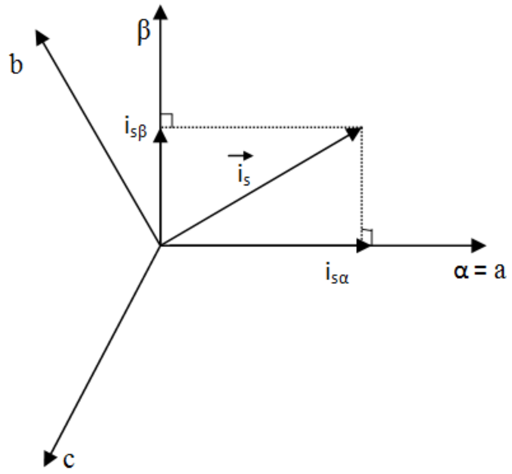


Figure 2: Current vectors and components along α & β axes [1]

Projection of the three current vector components (a, b, c) along the α and β axes can be represented as:

$$is\alpha = ia$$

$$is\beta = \frac{1}{\sqrt{3}}\, ia + \frac{2}{\sqrt{3}}\, ib$$

1.4 Park Transformation

This is one of the key transformations applied in field oriented control, it is a tensor that rotates the frame of reference of a three-element vector. This mathematical tool is used to project the α and β phases obtained from Clark Transform onto d and q axes to make it an independent of time frame of reference [1].

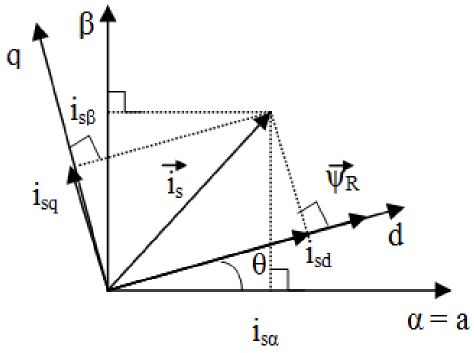


Figure 3: Current vectors and components along α-β axes and along d-q axes [1]

The projections of stator currents along α-β axes onto the d-q axes can be represented by:

$$i_{sd} = i_{s\alpha}\cos\theta + i_{s\beta}\sin\theta$$

$$i_{sq} = -i_{s\alpha}\sin\theta + i_{s\beta}\cos\theta$$

θ: Flux Position

1.5 Inverse Park Transformation

The above mentioned mathematical tool is used to obtain desired/reference stator voltage components along the α-β axes from the desired/reference stator voltage components along d-q rotating frame of reference [1]. The output signals from the inverse park transform then go as input into Space Vector Pulse Width Modulation.

Mathematical equations most commonly used:

$$v_{s\alpha ref} = v_{sdref}\cos\theta - v_{sqref}\sin\theta$$

$$v_{s\beta ref} = v_{sdref}\sin\theta + v_{sqref}\cos\theta$$

θ: Flux Position

1.6 Space Vector Pulse Modulation

Voltage from the DC source is delivered to the PMSM motor drive via three-phase inverter with six transistors, each of the three phases can be in either of the two states hence giving us 2^3 which is equal to 8 states. SVPWM is hence an algorithm developed for the creation of alternating current [1]. Upper and lower switch should always be driven by complimentary signals. All of the possible switching combinations are shown in the figure 4:

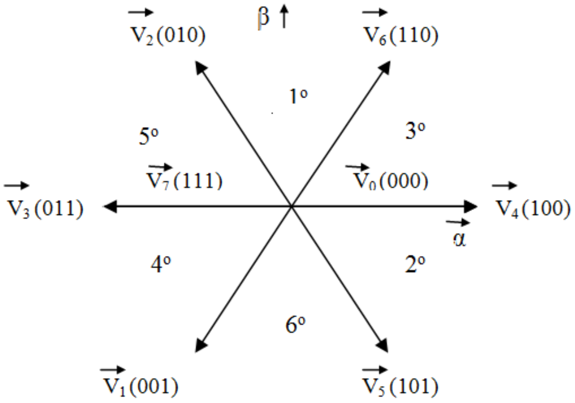


Figure 4: Switching vectors [1]

As seen the eight base vectors take up the shape of a hexagon, with a phase difference of 60 degrees among different vectors, the vectors divide the plane into six sectors and based on the sector onto which the reference voltage falls nearest to that particular sectors voltage signals are considered as the active voltage vectors, another crucial element is the time for the active voltage vectors will stay on to achieve the desired voltage [1].

1.7 Approach and Thesis Outline

The objective of this project is to develop a Fault tolerant power conversion system with interleaved hybridized energy storage system for a PMSM traction motor drive used in electrified vehicles to be able to detect as well as rectify faults induced in AC-DC bridge rectifiers or DC-AC bridge inverters used in PMSM motor drives to convert alternating current produced by an electric generator during regenerative braking to required direct current to charge the battery **or** to convert direct current from the battery to alternating current as required by the motor drive to propel the vehicle.

This project deals with the applications associated with Integration of power electronics into electrified powertrains because of the fact that reliability of these power electronic circuits is of utmost importance for continuous operation of electrified vehicles in case of a simple switch failure. Amongst the most common faults that might occur in power electronics, work in this project is entirely focused on switching faults which could either be open-circuit or short-circuit faults.

Open-circuit faults are mainly induced due to an opening in the circuit mainly due to failure in the switching devices to conduct as a result of which a very high resistance to current flow is developed, short-circuit faults are mainly induced if both switching devices in one of the legs of the rectifier are turned on due to either a failure in the control logic or physical failure of the switching device as a result of which there is minimum resistance to current flow and a very high magnitude of current starts flowing through the leg, this results in extremely high values of heat dissipation. This would result in thermal runaway causing a catastrophic failure of the entire device in a very short period of time.

This project provides a solution to overcome switching device failure in one of the legs of the bridge rectifier. This is achieved by using interleaved bi-directional DC-DC converter instead of a conventional DC-DC converter and in case of a switch fault detection a control strategy has been developed to switch from the fault induced phase on the bridge rectifier to the additional leg on the bi-directional DC-DC converter. The other advantages of the suggested model being reduced load on the inductors of the DC –DC converter as there would be two of them sharing the load, this also results in reduced heat rejection losses. The current ripple would be reduced by a significant value to almost DC as both the currents are phase-shifted by 180 degrees.

The three phase currents are constantly being sensed, a control strategy has been developed to detect switch faults from the three measured currents. On fault detection, rectification strategy replaces the fault induced switches by switches on the additional leg of the DC-DC converter.

The software used for building circuits of the PMSM motor, DC-DC Converter and for simulating various conditions is PSIM**.**

Chapter 2: Proposed Approach and Results

2.1 Permanent Magnet Synchronous Motor

Permanent magnet synchronous motors consist of a permanent magnet embedded into the rotor, this could either be a permanent magnet or it could be a winding coil excited with DC current, this is usually done as PMSM motors are not self-starting. The stator comprises of windings that are connected to an AC supply to produce a rotating magnetic field which then interacts with the magnetic field of the rotor to essentially lock the two interacting magnetic fields together at synchronous speed. The speed thus remains constant independent of the load acting on the motor provided the external torque acting on the motor is lesser than the maximum torque the motor can produce. A fast running physics based model of the PMSM motor with feed-forward estimation and feedback control was developed on PSIM as shown below in figure 5.

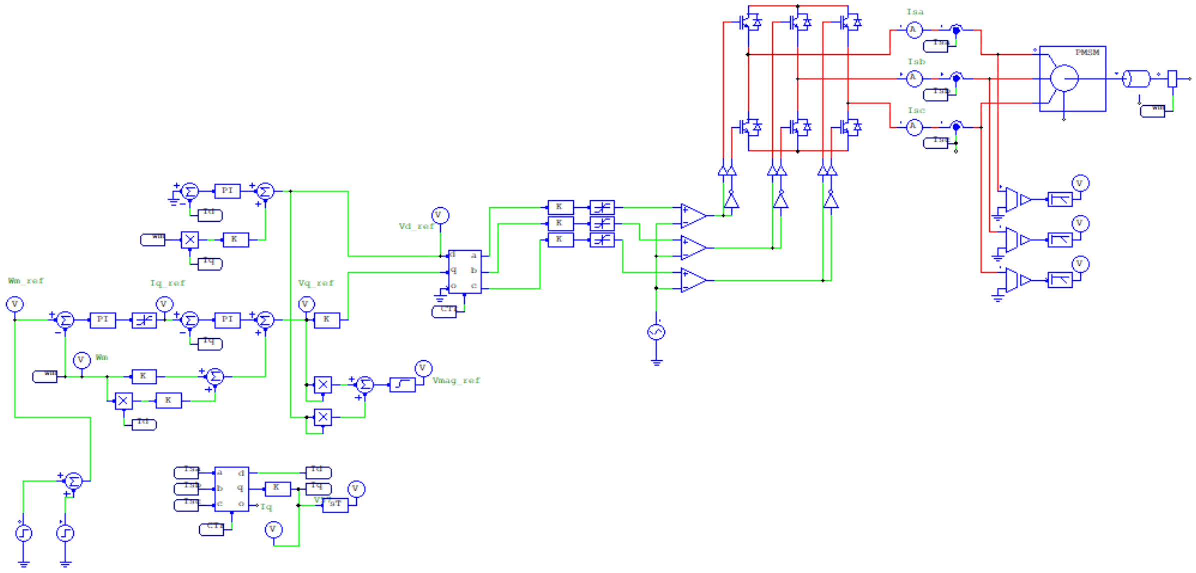


Figure 5: PMSM motor drive

2.2 Bi-directional DC-DC Converter

Boost converter is essentially a step-up converter that is used mainly to step-up the output voltage as compared to the input voltage, it comprises of at least two semiconductors them being a diode and a transistor, they also comprise of energy storage devices such as inductors and capacitors to reduce voltage ripple.

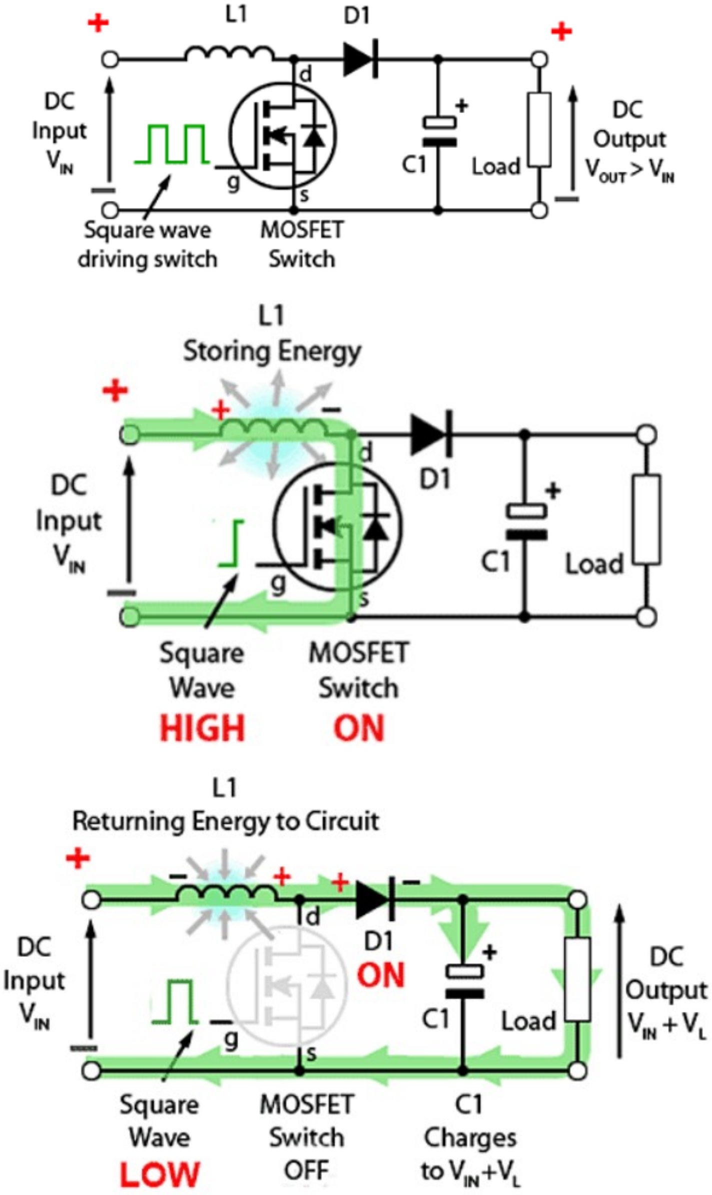


Figure 6: BOOST converter along with topological state

2.2.1 Working Principle

The figure 6 illustrates the operating principle of the converter, during the time period where the duty ratio is high the MOSFET is conducting as a result of which there is an effective short between the right hand side of the inductor and the negative terminal of the supply. Hence current flows through the inductor storing electrical energy in its magnetic field. When the duty ratio goes low, the MOSFET turns off as a result of which both the input voltage and the voltage produced by the inductor as a result of the energy stored in its magnetic field forward bias the diode causing current to flow through to the load:

- Rate of change of current when switch is on being: $(\Delta I/\Delta t) = (Vin/L)$
- Rate of change of current when switch is off being: $(\Delta I/\Delta t) = (Vin-Vo/L)$
- Since the average current flowing across an inductor in a cycle should be zero, this means $(Vin/L)*DT + (Vin-Vo/L)*(1-D)T = 0$.
- On simplification we get:
  - $Vin=Vo*(1-D)$, D being the duty ratio.
  - As the value of D is increased the output voltage keeps increasing with respect to input voltage.
  - The physics based model of the DC-DC Buck Boost Converter was developed on PSIM and is shown in figure 7, Interleaved Converters were chosen as they offer a lot of advantages such as:
    - They reduce the I^2R losses by 50%, as the current flowing through each inductor is halved
    - The output ripple of current is smoothened to almost a steady DC current, this is achieved by phase shifting the current at the input to the second leg by 180 degrees

- In case of a switching failure in one of the legs of the bridge rectifier used in the PMSM motor drive, it could be replaced by one of the legs of the converter.

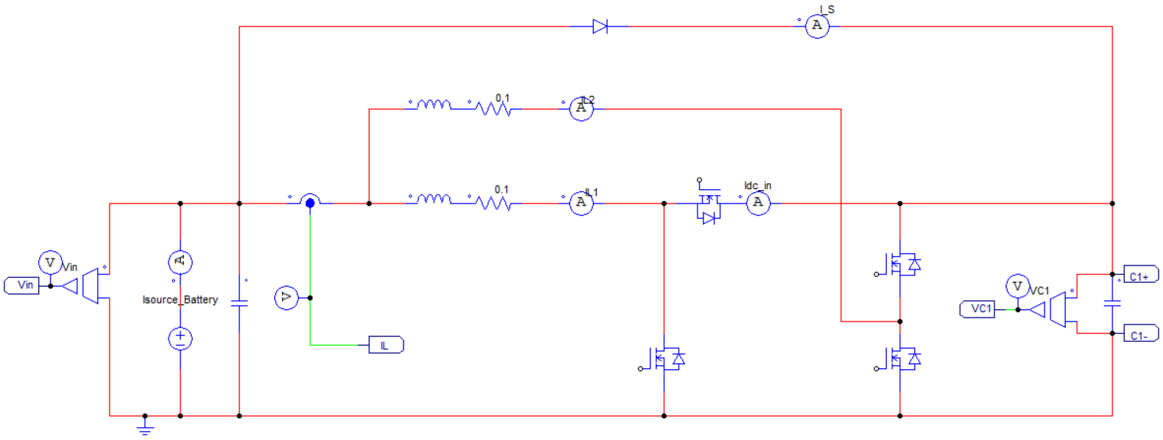


Figure 7: Interleaved DC-DC converter [3]

2.2.2 Control Logic

A control logic was developed to individually control MOSFET's on both legs of the bi-directional DC-DC converter as shown in figure 8. PI controller gains were tuned to determine the ideal duty ratio values based on the difference between the present output voltage values and the commanded output voltage.The difference in the voltage is initially converted to desired current, which is then compared with the line current and the difference is sent to another PI controller which converts the difference in currents to the required duty ratio and this signal is then transmitted to all of the power switches.

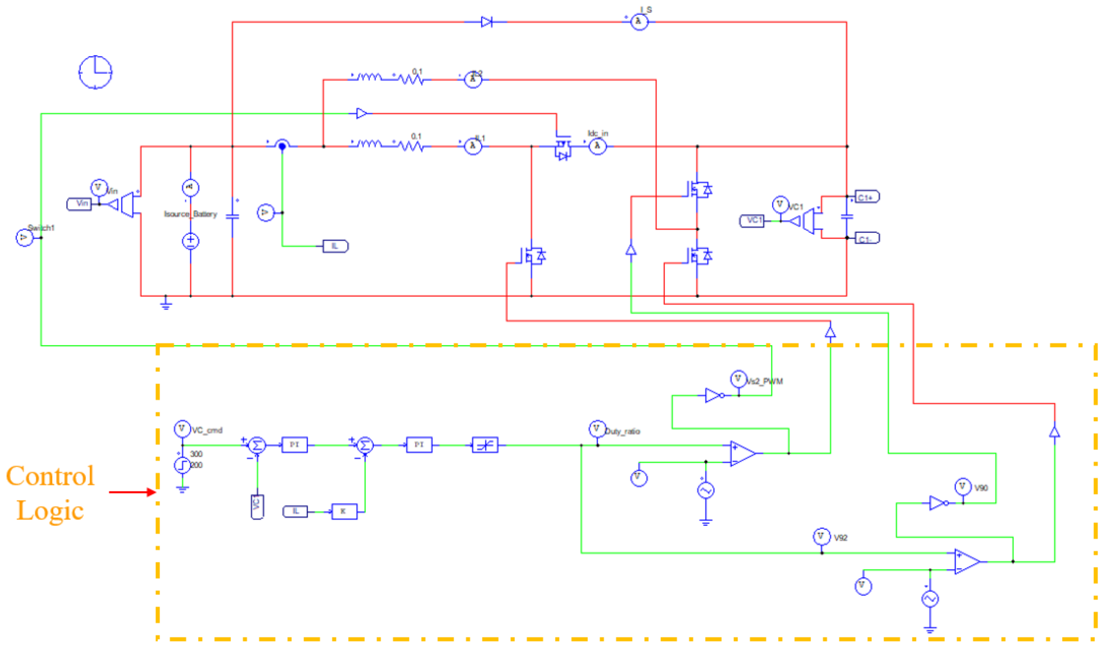


Figure 8: DC-DC converter model coupled with controller

2.2.3 Integration Results

The interleaved bi-directional DC-DC converter was integrated with the PMSM motor drive as shown in figure 13. The objective of this exercise is to verify if change in the request torque from the motor translates to change in the duty ratio of the Buck-Boost Converter, this is achieved by commanding higher voltage on the Buck-Boost Converter and ensuring there is a change in the duty ratio, which then translates to increase or decrease of the current magnitudes.

The figure below shows the overall architecture and the circuit diagram of the integrated DC-DC converter and PMSM motor drive model along with their individual controllers:

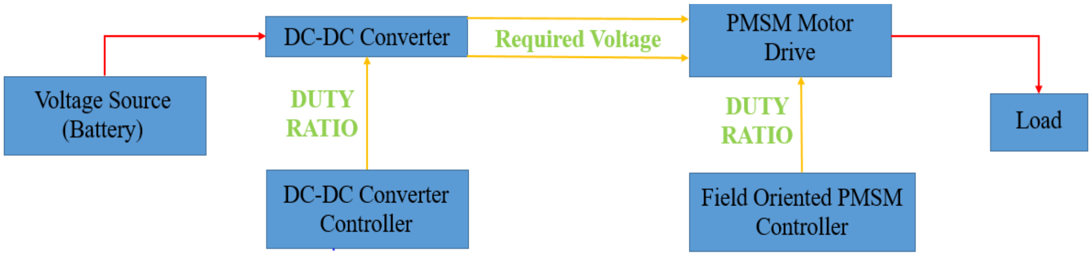


Figure 9: Architecture of the integrated setup

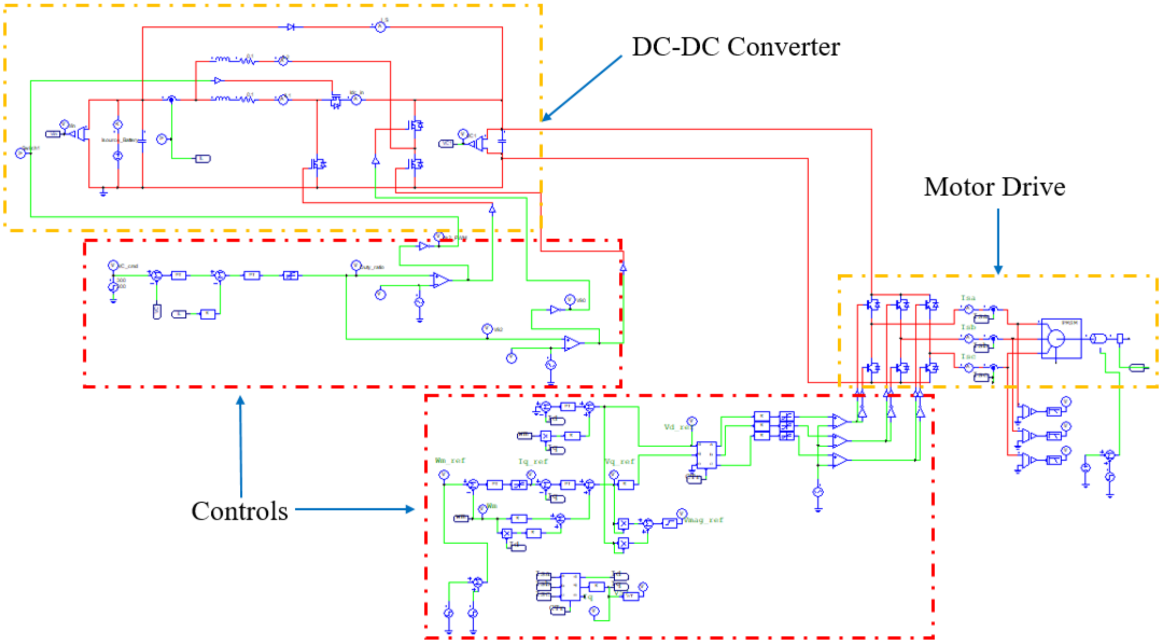


Figure 10: Circuit diagram of the integrated setup

Inputs to the simulation:

- ○ Request voltage was increased 200 to 300V at zero seconds
- ○ Change in desired angular velocity from 85 to 95 rad/s at 2.5 seconds

Output waveforms of duty ratio and current are plotted below:

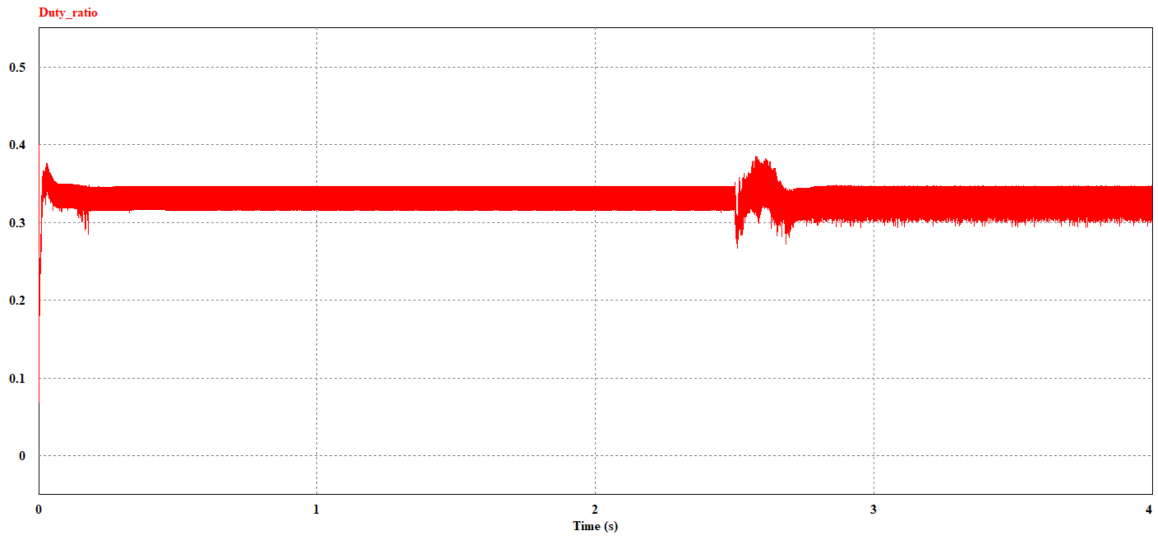


Figure 11: Duty ratio

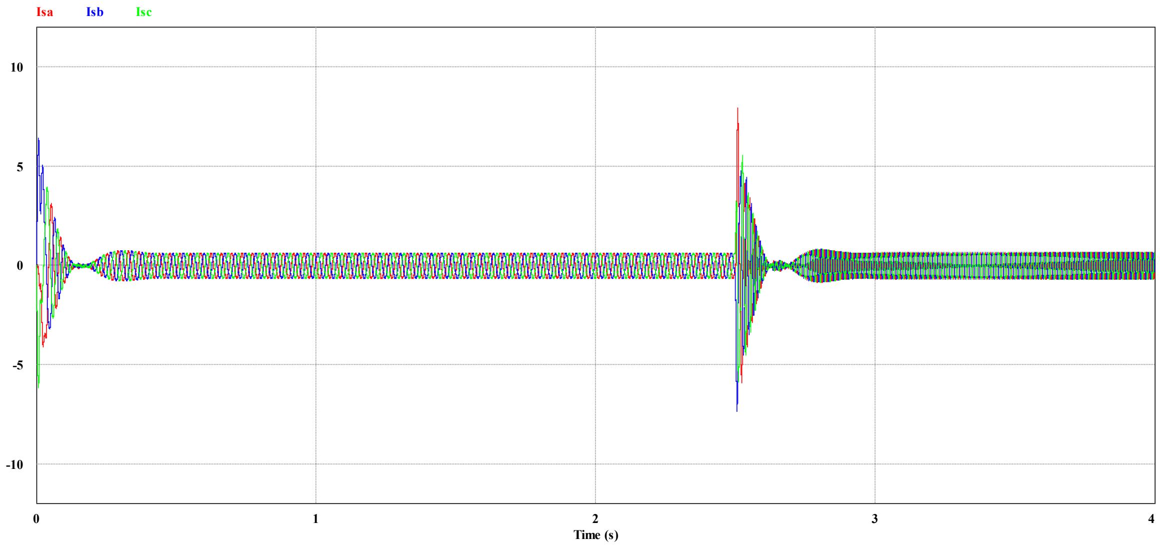


Figure 12: Motor drive phase currents

2.3 Detection of Switching Faults

2.3.1 Detection

Power-switching faults account for a significant value when it comes to inverter faults, they represent 34% of the overall faults that might occur in an inverter. They are mainly classified into open-switch and closed switch faults, the diagnostics of such faults are mandatory as they can be detrimental to the entire electrified powertrain of the vehicle. There are a lot of applications wherein continuous operation of these components is mandatory and hence a fault tolerant system capable of fast-detection, followed by isolation and rectification has been developed to ensure continuous operation. Over the years, a lot of techniques have been developed with the objective of detecting and isolating these power-switching faults, they can be mainly classified into signal based methods, Park's vector based method and observer base method [7].

The contributions being, first a new detection strategy has been developed followed by a control strategy to rectify either an open circuit fault. The detection strategy is based of computing and monitoring normalized average current values every time step, the advantage of this methodology is that there is no need for any information regarding the system model, hence calibration and integration of this setup into the controller for real-time operation would be simple. The biggest advantage of this process being detection strategy is independent of the load acting on the motor drive. The biggest disadvantage being it is mainly oriented for working with open-circuit faults as the detection time is quite high around 0.02 seconds.

2.3.2 Open-Circuit Fault Induction and Simulation Results

Switching faults were induced in the PMSM motor drive circuit to simulate real-time switching faults induced in motor drives, faults were induced by developing a simple circuit using logic gates and step functions as shown below, the control logic going into the power-switches were cut-off at 3 seconds to simulate an open-switch fault defect. The step-input signal goes down from 1 to zero at 3 seconds which then feeds into the AND Gate whose other input is the control logic that feeds into the MOSFET’s.

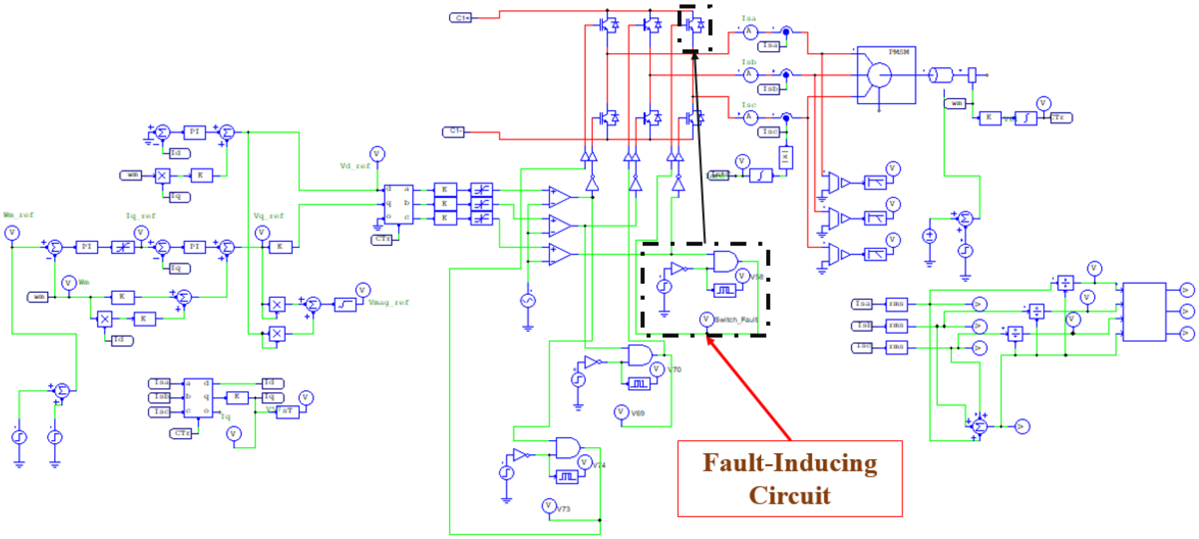


Figure 13: Integration of DC-DC converter to the PMSM motor drive circuit

The results of the simulation after inducing the fault are shown below:

- The fault was induced at 3 seconds in the upper switch at Phase C, hence there is an open-circuit fault in the third phase of the bridge rectifier as seen in figure 24, the logic from the controller is cut-off and the switch is permanently turned-off to simulate open-circuit fault.
- The figure 14 below shows that the positive half of Phase C current is clipped off as the upper switch of the third leg of the bridge rectifier is turned off to simulate open-circuit

failure condition, clearly this would completely deteriorate the performance and hence a control strategy has been developed to detect and rectify open-circuit switch failures

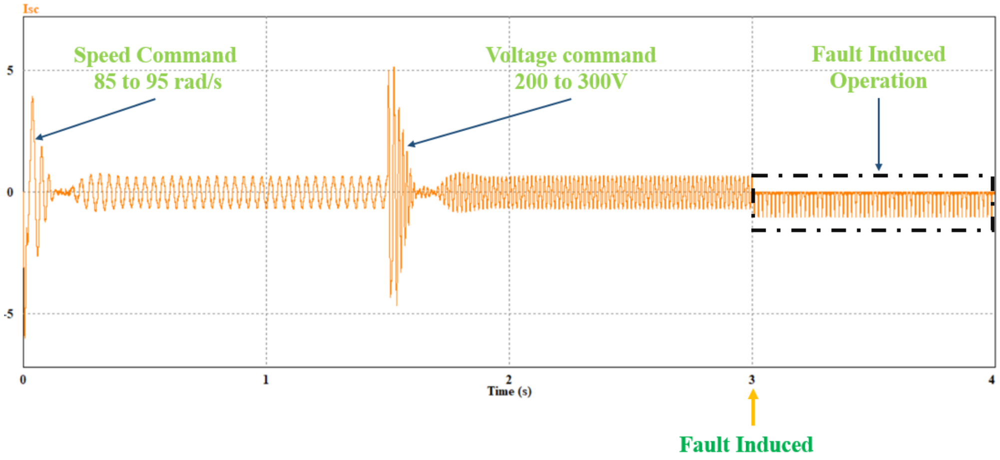


Figure 14: Phase current C (Fault Induced)

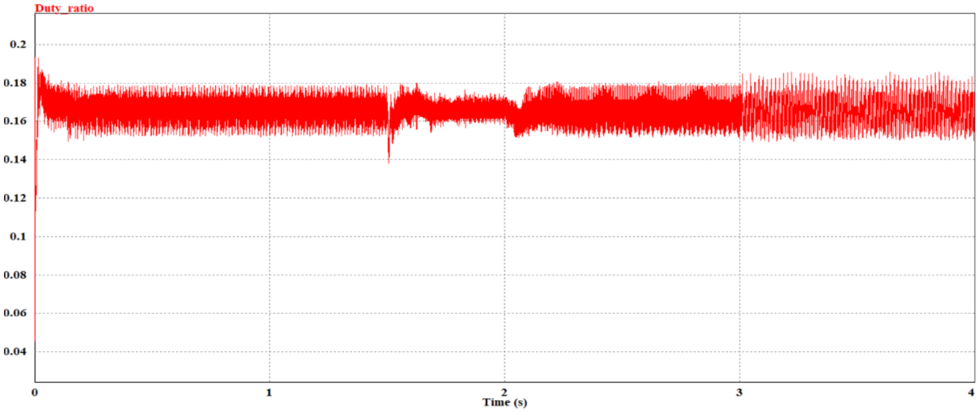
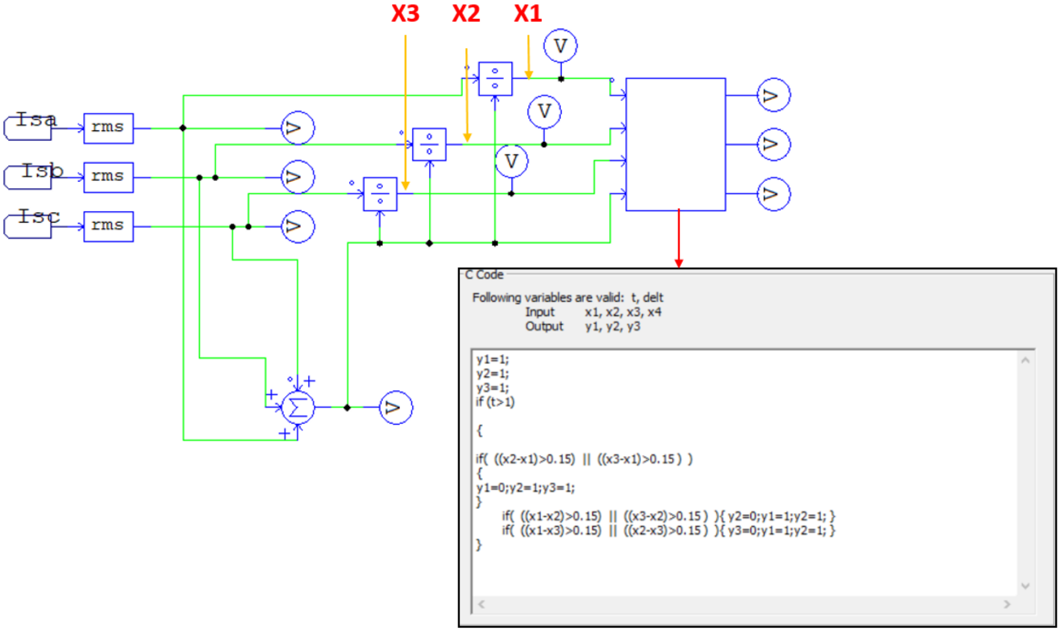


Figure 15: Duty ratio (Fault Induced)

2.3.3 Detection Strategy

Detection of fault - induced switches is based on computing and normalizing all of the three phase currents at every simulation time step.

- Three diagnostic variables X1, X2, X3 are defined, each corresponding to the RMS value of the current divided by the sum of RMS currents of all the three phases.
- As we are computing the RMS value of each of the phase currents at every time step and dividing them by the sum of RMS currents, we essentially make X1, X2 & X3 independent of the load, which makes detection based on the diagnostic variables independent of the load. X1, X2 & X3 are defined below:
    - X1= ((Ia_RMS) / ((Ia_RMS)+(Ib_RMS)+(Ic_RMS)))
    - X2= ((Ib_RMS) / ((Ia_RMS)+(Ib_RMS)+(Ic_RMS)))
    - X3= ((Ic_RMS) / ((Ia_RMS)+(Ib_RMS)+(Ic_RMS)))
- A simplified C-code was coded on PSIM to capture the diagnostic variables X1, X2 & X3 as shown below:



```
Following variables are valid:  t, delt
            Input       x1, x2, x3, x4
            Output      y1, y2, y3
```

```
y1=1;
y2=1;
y3=1;
if (t>1)

{

if( ((x2-x1)>0.15) || ((x3-x1)>0.15 ) )
{
y1=0;y2=1;y3=1;
}
    if( ((x1-x2)>0.15) || ((x3-x2)>0.15 ) ){ y2=0;y1=1;y2=1; }
    if( ((x1-x3)>0.15) || ((x2-x3)>0.15 ) ){ y3=0;y1=1;y2=1; }
}
```

Figure 16: Fault detection strategy

2.3.4 Simulation Results

The simulation results shown below compare the behavior of diagnostic variables under normal operating conditions as compared to switching fault-induced operation:

- As seen from the simulation results in figure 17 & 18, the values of X1, X2 & X3 remain constant independent of load or speed changes, except when there is a switch fault. The initial few fluctuations are a result of initialization of the PSIM software
- As the upper switch on Phase C was forced to simulate an open switch fault condition at 3 seconds, this is when the diagnostic variable X3 tends to drop and since there is a feedback speed control on the PMSM motor model, the diagnostic variables X1 & X2 tend to increase as Ib & Ic increase to make up for reduction in Ic.
- Based on the simulation it can be seen that the difference between X1 and X2 as compared to X3 is greater than 0.15 only if there is an open switch fault in phase C and does not

change significantly during load change request or speed change request. Hence the detection strategy is based on the above inference that fault is detected when:

(X1-X3)>0.15 && (X2-X3)>0.15

- Under normal operating conditions**:**

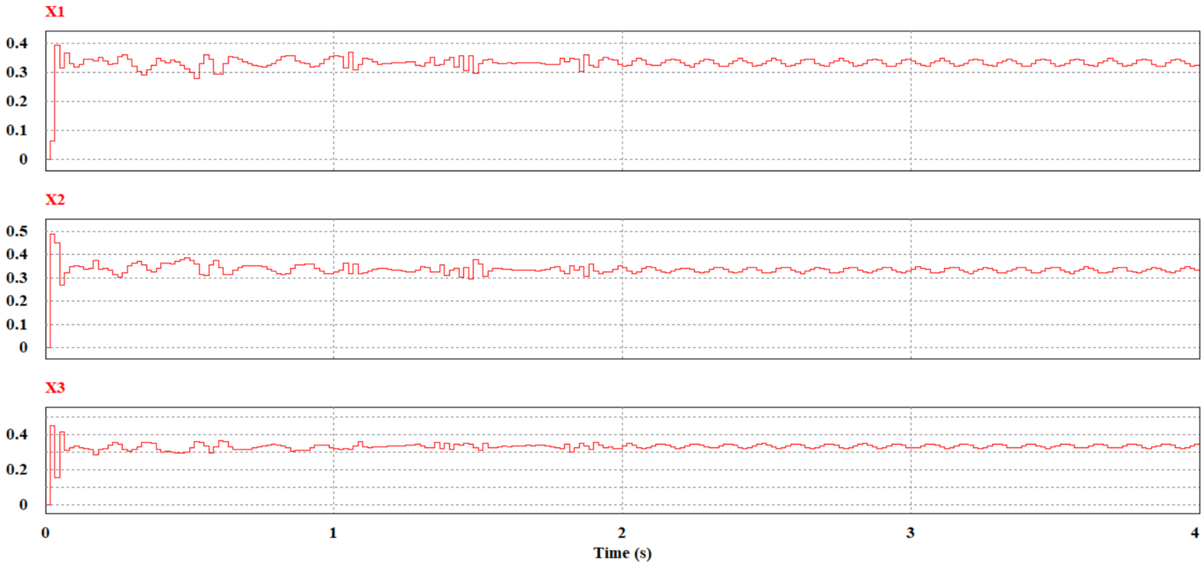


Figure 17: Diagnostic variables (Normal Operation)

- Under fault-induced operation**:**

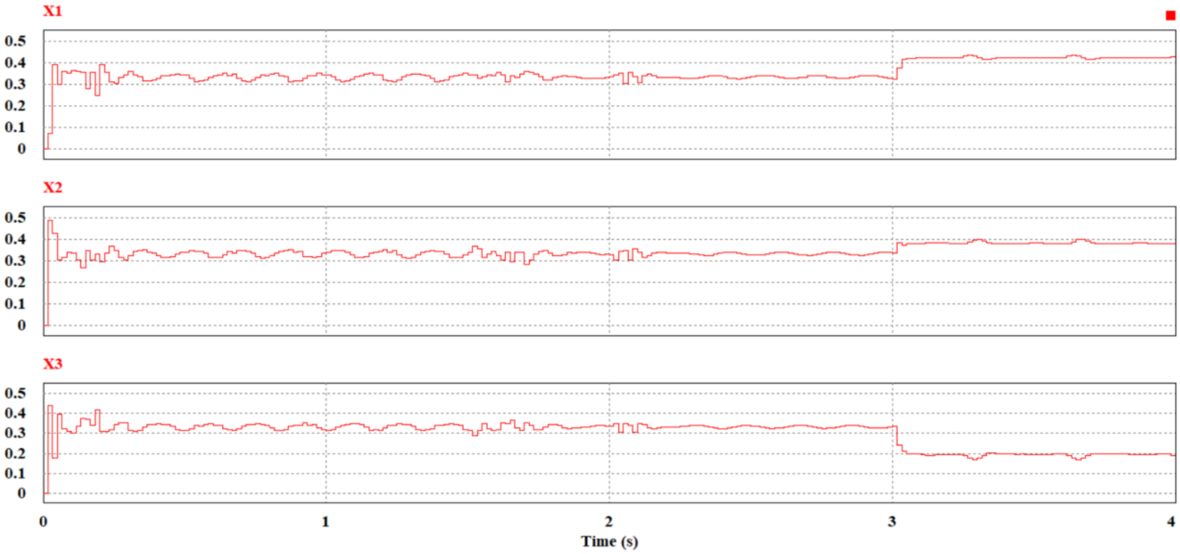


Figure 18: Diagnostic variables (Fault-Induced Operation)

2.4 Rectification of Switching Faults

2.4.1 Rectification

Rectification of switching faults in key to ensure reliable and continuous operation of these electrified powertrains. The concept of rectification in this project is achieved by replacing the entire leg/phase in which the fault is induced by one of the two legs of the interleaved by directional DC-DC converter, the whole process of detection and rectification takes about 20ms during which the components involved are not affected. This suggested model offers a lot of advantages, them being:

- During normal operation, the interleaved structure of the bi-directional DC-DC converter helps in reducing the load on each inductor, hence increasing the reliability.
- The losses as compared to a conventional bi-directional DC-DC converter are reduced by 50%, as losses are directly proportional to the square of the current flowing through the inductor.

- The output ripple in the current waveform is significantly reduced as compared to a conventional DC-DC Converter.
- During switching failures, there is an additional leg to replace the defected phase/leg in which the fault is detected.

2.4.2 Rectification Strategy

Fault Detection based on the three diagnostic variables X1, X2 & X3 as explained in the previous section. On detection of the fault, the control strategy cuts off the control signals to the faulted phase leg as a result of which both the switches on the faulted phase are cut-off. The control signals from the Buck-Boost converter controller going in to the additional leg of the buck-boost converter are cut-off and are simultaneously replaced with the control signals of the faulted switch from the PMSM motor drive controller.

A circuit has been developed to ensure connection for current flow between the legs of the bridge rectifier and the additional leg on the Buck-Boost converter to replace the faulted leg on the bridge rectifier with the additional leg on the Buck-Boost converter, this circuit is activated only in case a fault is detected by the diagnostic variables. All of the control strategies for each of the above mentioned steps are developed on simplified C-Blocks on PSIM, into which the control logic is fed as a C-Code. Figure 19 shows the entire circuit model comprising of the detection strategy, the rectification strategy along with all the necessary connections to ensure continuous and reliable operation in case of a switching failure, details of which have been explained in sections below.

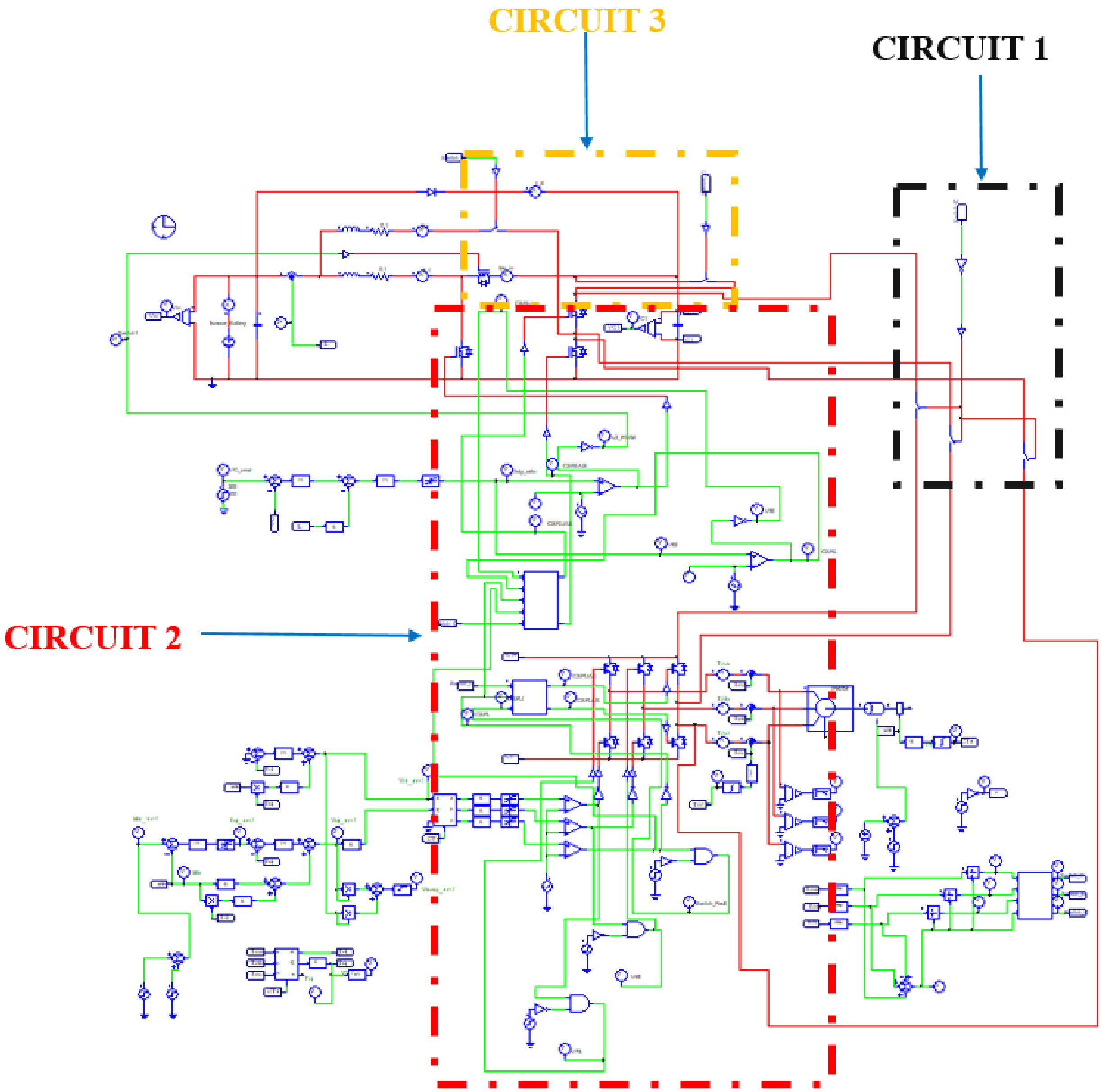


Figure 19: Detection and rectification implemented circuit diagram

As shown in the figure 20, circuit 1 is very crucial to ensure switching of faulted leg with rectified leg.

- Normal Operation:
  - Switching Signal_C is one during normal operation, hence the output of the NOT gate is zero, ensuring all the switches are open during this time.
- Fault-Induced Operation:
  - Switching Signal_C goes to zero as the fault is induced, as a result of which output of the NOT gate is one, hence all the switches are now closed and the current can now flow into the rectified leg on the Buck-Boost Converter instead of the faulted leg on the PMSM motor drive.

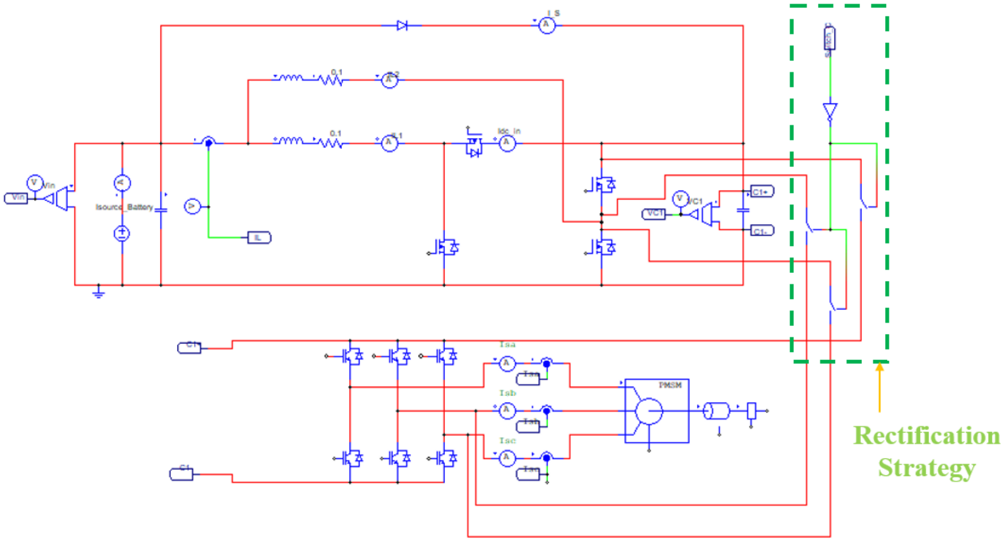


Figure 20: Circuit 1

As shown in the figure 21, circuit 3 is to isolate the rectified leg from the buck-boost controller circuit during faulted operation.

- Normal Operation:
  - ➢ Signal_C is one as there are no faults detected, as a result of which both the switches are closed and thus the additional leg (rectified leg) is a part of the Buck-Boost converter circuit.
- Fault-Induced Operation:
  - ➢ Signal_C is zero as a result of which both the switches are open and thus the additional leg now behaves as a rectification leg and thus is completely isolated from the Buck-Boost converter circuit.

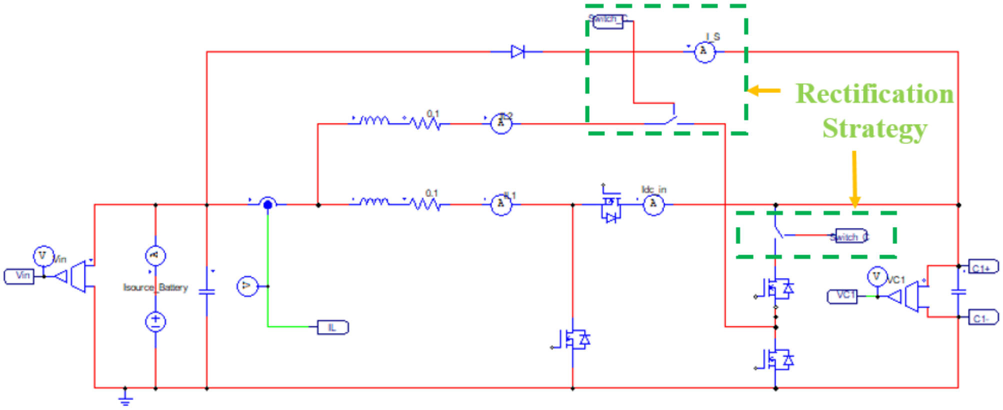
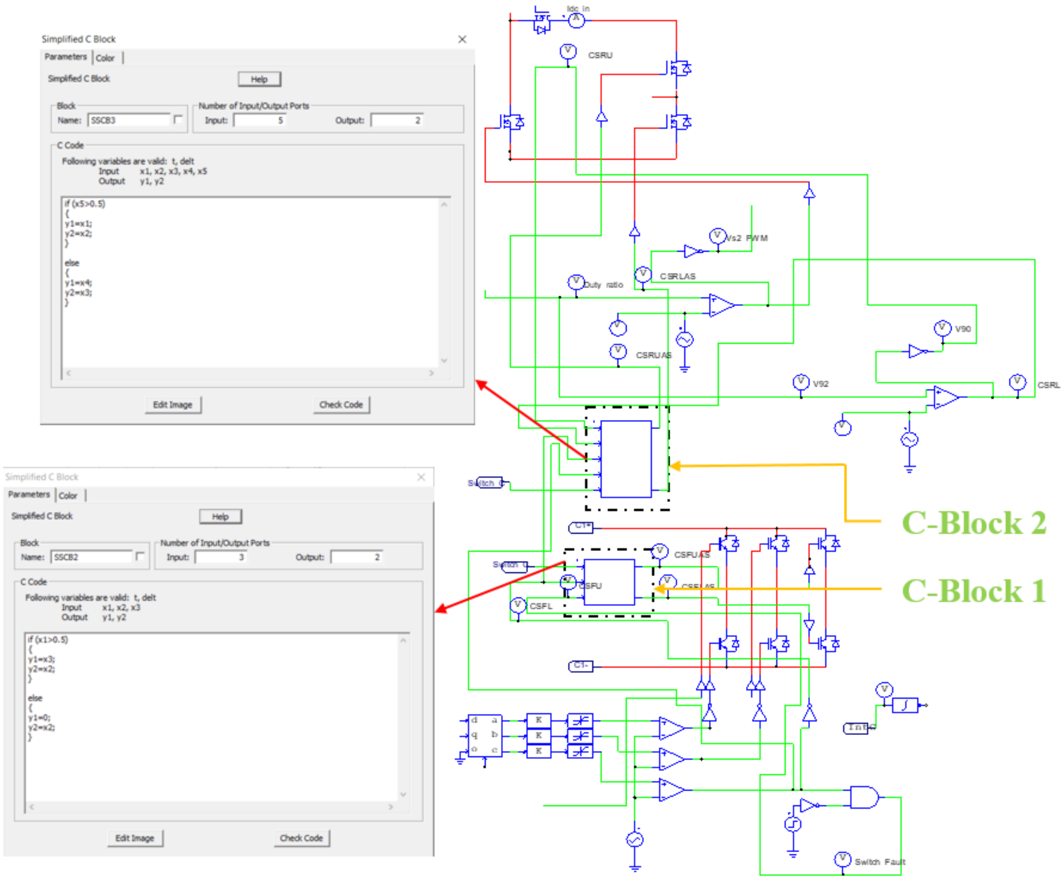


Figure 21: Circuit 3

As shown in the figure 22, circuit 2 is very critical to ensure the flow of logic. This circuit ensures that the right logic is flowing into each individual switch in both cases of normal operation and in case of a switching failure.

- Normal Operation:
  - C-Block 1: Ensures control signals coming in from PMSM motor drive controller feed into the switches on the bridge rectifier of the motor drive circuit as duty ratio signals.
  - C-Block 2: Ensures controls signals coming in from the buck-boost converter Controller feed into the switches on the additional leg of the DC-DC buck boost converter as duty ratio signals.
- Fault-Induced Operation:
  - C-Block 1: In case of fault detection based on the diagnostic variables, switch_C signal which is one of the inputs to the C-Block drops to zero, as the switch_C signal drops to zero, C-Block 1 cuts off the control logic signals coming in from the PMSM motor drive controller to the switches on the bridge rectifier that are now faulted to ensure all the electrical components on the motor drive circuit are safe-guarded.
  - C-Block 2: Ensures rectification of this fault to ensure normal, healthy operation of the motor drive. This is achieved by using another C-Block logic that switches the control logic signals going into the additional leg of the bi-directional DC-DC converter from the Buck-Boost converter controller to the PMSM motor drive controller. The switch in control signals occurs when the signal switch_C drops to zero.



Simplified C Block

Block Name: SSCB3

Number of Input/Output Ports Input: 5 Output: 2

C Code

Following variables are valid: t, delt
Input x1, x2, x3, x4, x5
Output y1, y2

```
if (x5>0.5)
{
y1=x1;
y2=x2;
}

else
{
y1=x4;
y2=x3;
}
```

Simplified C Block

Block Name: SSCB2

Number of Input/Output Ports Input: 3 Output: 2

C Code

Following variables are valid: t, delt
Input x1, x2, x3
Output y1, y2

```
if (x1>0.5)
{
y1=x3;
y2=x2;
}

else
{
y1=0;
y2=x2;
}
```

Figure 22: Circuit 2

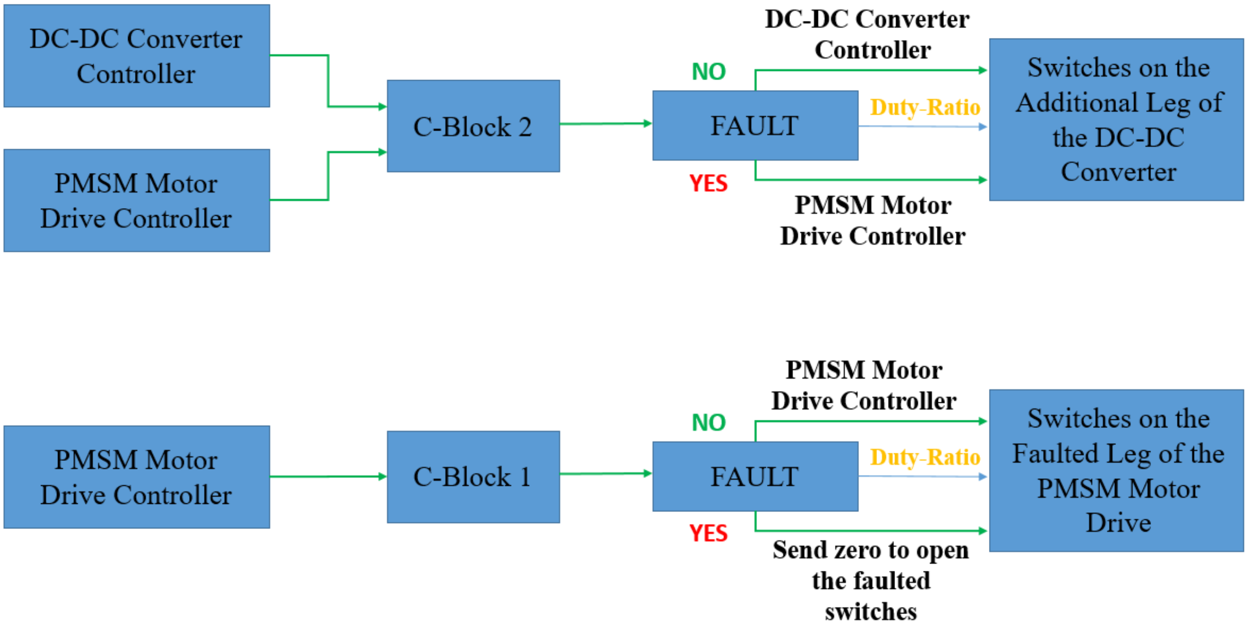
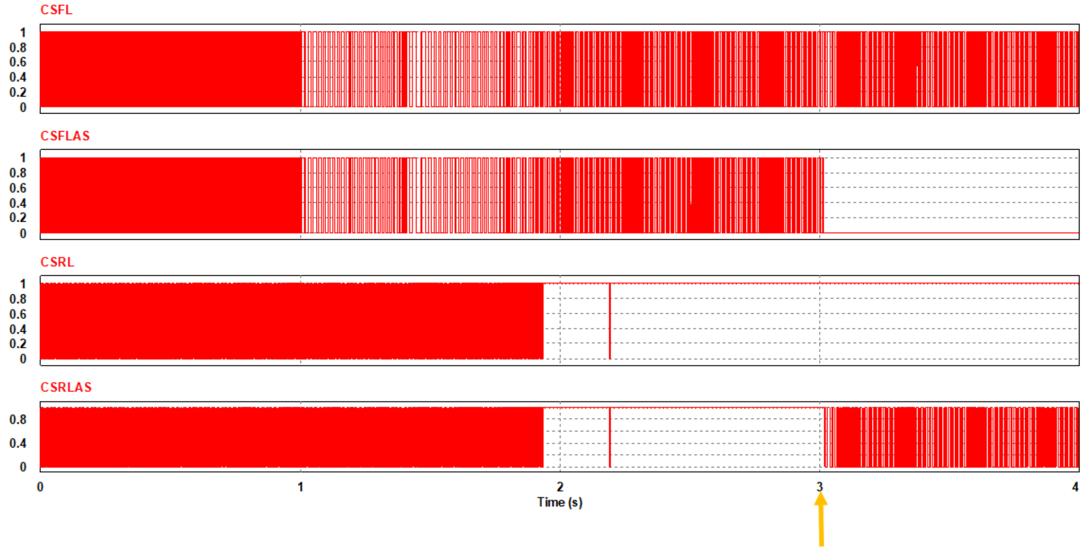


Figure 23: Circuit 2 logic flow

2.4.3 Simulation Results

Results shown in the figure 24, explain the switching of control logic in the event of a fault detection, this is achieved mainly because of circuit 2. As seen in the event of a fault detection (in this case fault is induced at 3 seconds) the control signals to the faulted phase in this case phase 3 are cut-off completely and the control signals going into the additional leg on the buck boost converter are replaced from the buck boost converter controller to the PMSM motor drive controller signals.



Fault Induced

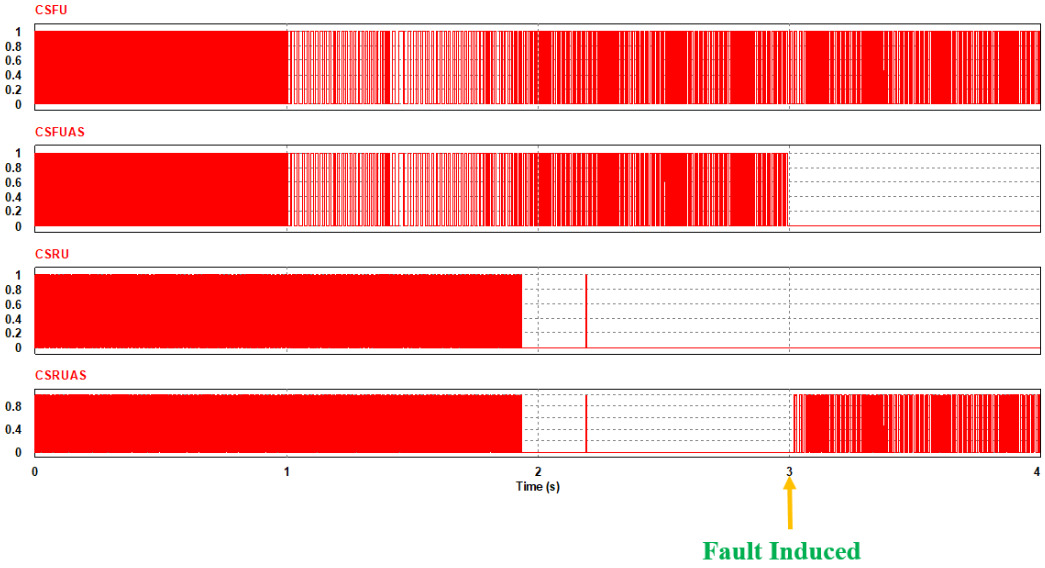


Figure 24: Control signals for upper and lower switches

Legend:

- CSFL: Control signal going into the lower switch on the phase in the motor drive into which the fault was induced.
- CSRL: Control signal going into the lower switch on the additional leg of the buck-boost converter
- CSFLAS: Control signals going into the lower switch on the phase in the motor drive into which the fault was detected, after rectification occurs.
- CSRLAS: Control signals going into the lower switch on the additional leg of the buck-boost converter, after rectification occurs.
- CSFU: Control signal going into the upper switch on the phase of the motor drive into which the fault was detected.
- CSRU: Control signal going into the upper switch on the additional leg of the buck-boost converter

- CSFUAS: Control signals going into the upper switch on the phase of the motor drive into which the fault was detected, after rectification occurs.
- CSRUAS: Control signals going into the upper switch on the additional leg of the buck-boost converter, after rectification occurs.

As seen from the graphs:

- During normal operation control signals from the PMSM motor drive controller feed into the switches on the motor drive and the buck-boost controller signals feed into the switches on the buck-boost converter.
- During fault-induced operation control signals going into the switches on the fault detected phase (Phase 3) are completely cut-off as a result of which CSFLAS & CSFUAS go to zero and as seen the control signals going into the additional leg on the buck-boost converter from the buck-boost controller are replaced by the control signals from PMSM motor drive controller signals, CSRLAS goes from following CSRL till 3 seconds, after which CSRLAS follows CSFL, same trend is followed with the control logics associated with the upper switch of the faulted phase (Phase 3), i.e. CSRUAS initially follows CSRU till fault is induced, after which CSRUAS follows CSFU . This goes to show that even though there is a fault in one of the switches on the bridge rectifier they are replaced by the additional leg on the buck-boost controller ensuring continuous operation without any failure or damage to any of the other electrical components on the circuit.
- The fault detection flag is associated with the switch_C signal as shown in figure 25, this signal is continuously monitored and calculated every simulation time step, whenever there is a fault detected by the diagnostic variables switch_C signal drops from 1 to 0.
  - 1 indicating normal, healthy operation.

- 0 indicating fault-induced operation

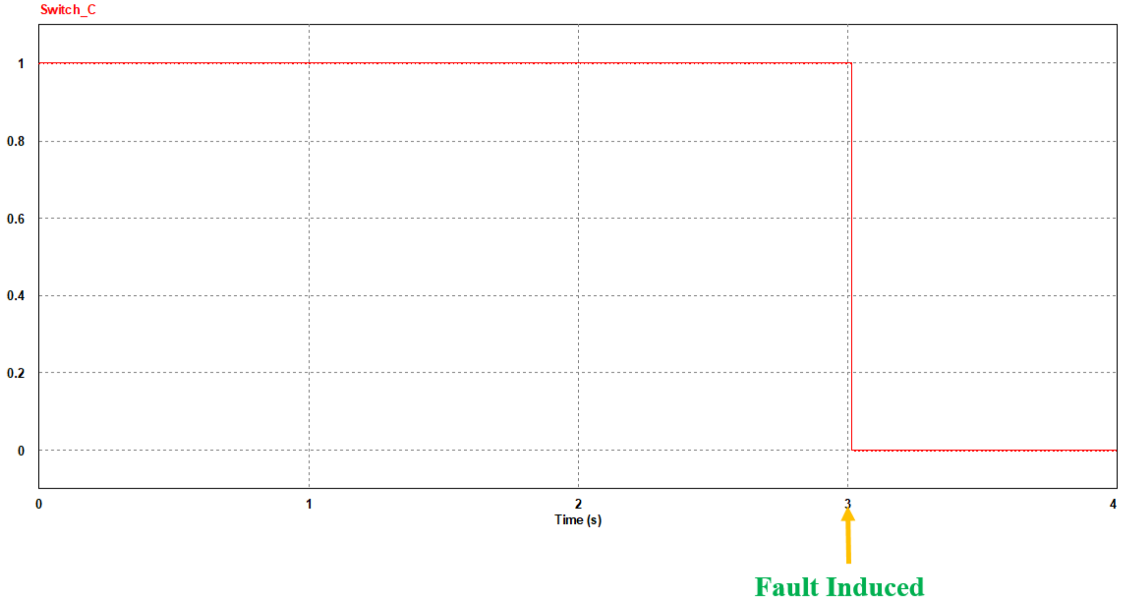


Figure 25: Flag for fault detection

Results shown in the figure 26, explain the switching control logic in the event of a fault detection, this is achieved mainly because of Circuit 1 and Circuit 3.

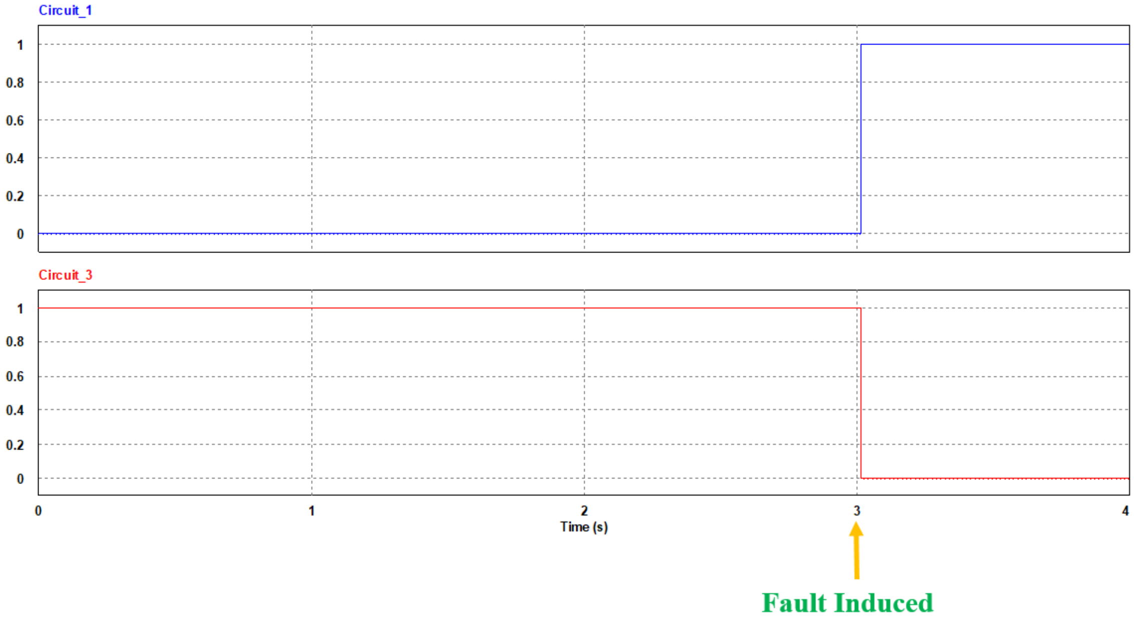


Figure 26: Switch states on circuit 1 & 3

As seen from the graphs

- In case of a fault detection which is at 3 seconds, circuit 1 ensures all the switches connecting the bridge rectifier phase legs to the additional leg on the buck-boost converter are closed to ensure the current in the faulted phase can continue to flow without any interruption. Hence at 3 seconds the signal for circuit 1 drops from zero to one.
- In case of a fault detection which is at 3 seconds, circuit 3 ensures the additional leg of the buck-boost converter now has to behave as a rectification leg and support the bridge rectifier circuit as it has one faulted leg, in order to replace the entire faulted leg with the additional leg on the converter, the additional leg must completely be isolated from the converter circuit. Hence the switches coupling the additional leg to the converter are opened the instant there is fault detection, as a result of which the additional leg can now support the bridge rectifier.

2.4.4 Current Waveforms Comparison

Below shown are results comparing all of the three phase currents during normal operation, fault-induced operation without detection and rectification, fault-induced operation with detection and rectification. As seen from figure 27**,** in the event of a fault being induced during operation such as the condition shown where one of the switches in the bride rectifier fails in this case switching failure is induced in the upper switch of phase C, as a result the positive half cycle of the current is completely clipped off in Isc phase current. The PMSM motor drive controller tries to compensate for this by increasing the phase currents Isa & Isb.

- Normal Operation:

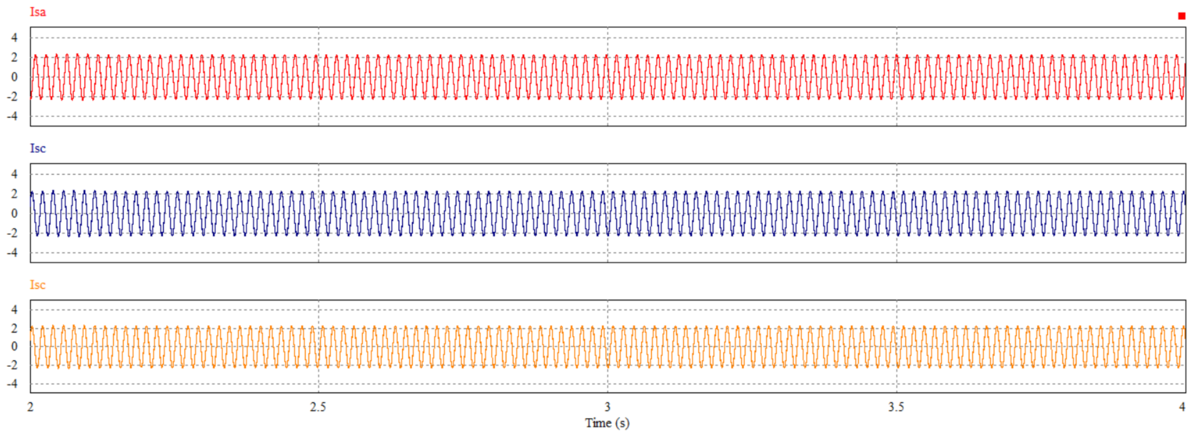


Figure 27: Current waveforms during normal operation

- Fault-induced operation without detection and rectification:

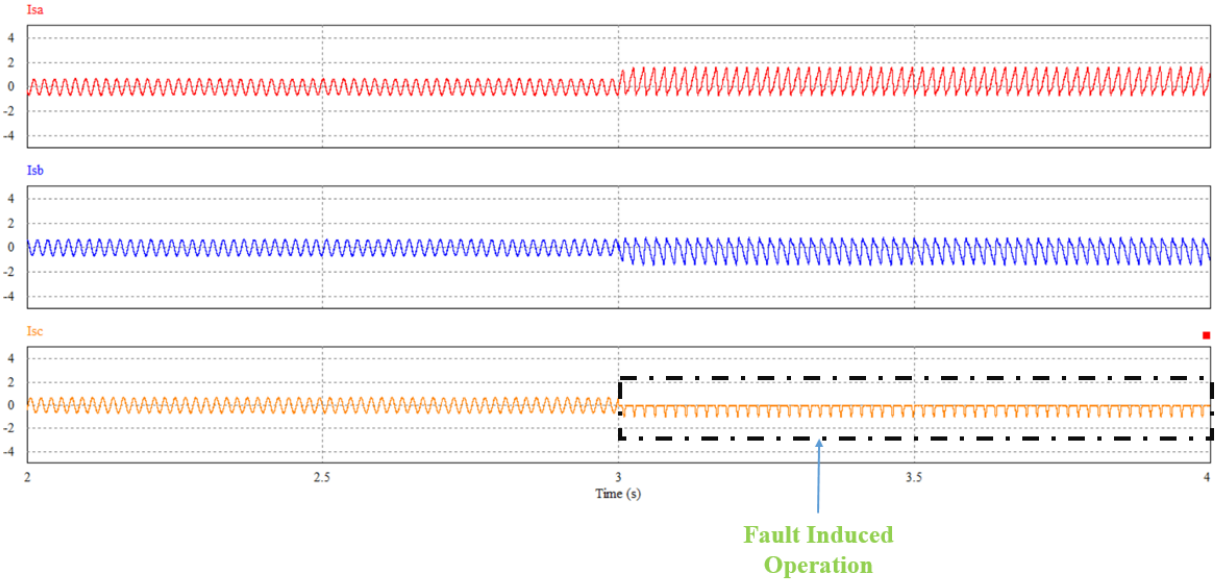


Figure 28: Current waveforms (Fault-Induced Operation)

- Fault-induced operation with detection and rectification:

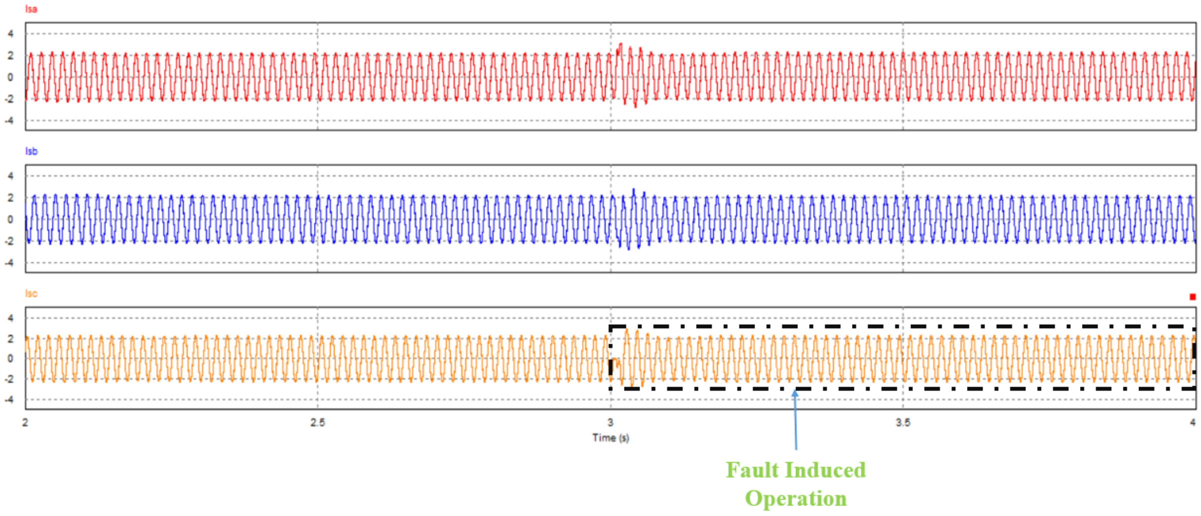


Figure 29: Current waveforms (Fault Detection and Rectification)

As seen from the results in figure 30 it takes around 20ms for fault detection and rectification after which the current waveforms stabilize back to normal operating conditions, this proves that even if a fault is induced, the circuit is capable of detection and rectification and is hence fault tolerant.

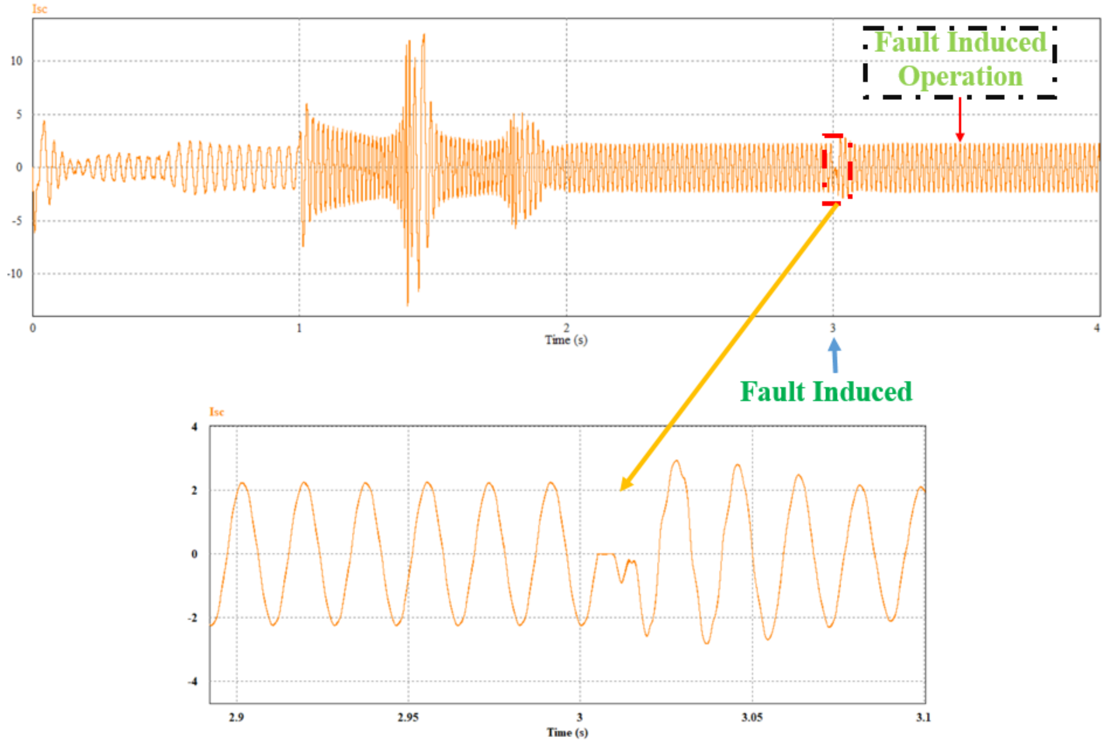


Figure 30: Phase C- current post-rectification

Chapter 3: Conclusion

The methodology developed has the capability of detecting and rectifying switching faults induced in the bridge rectifier used in PMSM motor drives. Hence ensuring continuous operation and reliable operation of the electrified powertrain even in the case of a switching failure. As seen from figure 22, on detection of failure at 3 seconds it takes around 20 ms for the diagnostic variable based detection strategy to detect the fault-induced in phase C of the motor drive circuit as a result of which the positive half cycle of phase C current is clipped off. However, after detection, rectification takes place ensuring the entire faulted phase leg of the motor drive is replaced by the additional leg on the DC-DC converter restoring the phase C current back to its original waveform. The architecture for fault detection and rectification shown here is just for one-phase or leg, however it is quite simple to extend this logic across all three phases of the bridge rectifier.

Integration of this circuit into motor drives would require 5 switches/phase along with a few additional control strategies, hence implementation of the suggested model will not be very expensive or complicated.

References

1. Texas Instruments Europe, “Field Orientated Control of 3-Phase AC-Motors,”1998. Available: https://www.ti.com/lit/an/bpra073/bpra073.pdf

2. Benslimane, T., "Analysis of Open-Switch Fault Two Level Three Phase Voltage Inverter Behaviour and Automatic Detection and Location Using Zero Harmonic Component," SAE Technical Paper 2007-01-1474, 2007, https://doi.org/10.4271/2007-01-1474.

3. L. Chen, "A variable voltage converter with direct bypass for traction drive inverters," 2013 IEEE Energy Conversion Congress and Exposition, Denver, CO, 2013, pp. 2793-2798.

4. Gupta, A, "Intelligent Control of Brushless DC Motors", Dearborn, 2014. Available:https://books.google.com/books/about/Intelligent_control_of_brushless_DC_motor.html?id=_wMoAQAAMAAJ

5. Karchnak, M., "High Power Semiconductor Switching," SAE Technical Paper 2006-01-3033, 2006, https://doi.org/10.4271/2006-01-3033.

6. M. Salehifar, R. S. Arashloo, M. Moreno-Eguilaz, V. Sala and L. Romeral, "A simple and robust method for open switch fault detection in power converters," 2013 9th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED), Valencia, 2013, pp. 461-468.

7. S. K. E. Khil, I. Jlassi, J. O. Estima, N. Mrabet-Bellaaj and A. J. M. Cardoso, "Detection and isolation of open-switch and current sensor faults in PMSM drives, through stator current analysis," 2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Tinos, 2017, pp. 373-379.

8. S. A. Gorji, H. G. Sahebi, M. Ektesabi and A. B. Rad, "Topologies and Control Schemes of Bidirectional DC–DC Power Converters: An Overview," in IEEE Access, vol. 7, pp. 117997-118019, 2019.

9. Yang, S., Chen, L., Alam, M., Xu, F. et al., "Switching Frequency Optimization of Boost Converter for HEV Applications," SAE Technical Paper 2017-01-1236, 2017, https://doi.org/10.4271/2017-01-1236.

10. Z. Jian-Jian, C. Yong, C. Zhang-Yong and Z. Anjian, "Open-Switch Fault Diagnosis Method in Voltage-Source Inverters Based on Phase Currents," in *IEEE Access*, vol. 7, pp. 63619-63625, 2019.