# Chapter 3

## Thermal Model Based Relaying Algorithm for Induction Motor Protection

### 3.1 Introduction

Induction motors are the robust machines as they can work under certain stress environment for example voltage variations, overload, and so on [151,152]. Though, these abnormal situations produce undue overheating and degradation of the stator winding electrical insulation. In fact, numerous studies have shown that about 30-40% of induction machine failures are because of the breakdown of stator winding [153-155], which makes insulation of the stator one of the most liable elements to overheating failures since its temperature limit is reached faster than the temperature limits of other motor components [156]. In this regard, winding protection becomes an essential task in order to ensure the safe operation of the induction motor and keep its lifetime [156-158]. For a suitable motor protection, different standards have been established. They define, among other things, the integral protection of rotatory machines, the degradation levels of the motor components, and their thermal protection limits [159-163]. For the latter, the maxima temperature levels by considering different classes of insulation systems are provided by the norms NEMA ( The National Electrical Manufacturers Association) [162], IEEE std. 1-200 [163], and IEEE std. C37.96 [159]. According to the standard IEEE std. C37.96, these values can be used to determine thresholds and trip alarms for excessive temperatures in stator and rotor [159]. Yet, these standards do not consider the thermal increment due to anomalies in the power source such as voltage unbalance. In order to protect the motor from the aforementioned perturbations, different investigations have been focused on the development of protection devices in which different methodologies and designs are used. Among them, devices such as relays [164,165], embedded processors [166, 167], thermal models [151, 158, 168], as well as methodologies based on stator resistance [169], acoustic-signal recognition [170], and the estimation of rotor temperature based on voltage and current signals [171, 172], have been presented in the literature. Despite obtaining promising results, the proposal of protection schemes that consider the different thermal impacts overtime, which are associated to the presence of different unwanted electrical or mechanical conditions (common conditions in industry applications), is still a demanding task.

## 3.2 Theoretical Background

### 3.2.1 Mechanical Overload and Voltage Unbalance on Induction Motors

Voltage unbalance and mechanical overload generate excessive overheating on induction motors [173, 174]. The overheating caused by these two phenomena is produced by an increment of current in the motor windings [156, 157]. This increment is demanded by the motor itself in order to maintain the torque in the rotor [152, 168]. Besides, a decrement in the rotor speed is obtained, generating an insufficient cooling [168]. The thermal increment negatively affects the motor lifetime, rotor and stator conductors, core, insulation, and bearings [156], producing irreversible damages [156, 157] when the motor heats beyond its design limits [168].

Voltage unbalance condition is presented when the voltage magnitudes of a three-phase system are unequal and/or differ from each other by a phase angle of 120 degrees [175]. Voltage unbalance can be evaluated using the voltage unbalance percentage (%UN) according to the IEEE std. 1159 [176]. It is defined as follows:

$$\% \text{ UN} = \frac{V_-}{V_+} \times 100 \tag{3.1}$$

where $V_-$ and $V_+$ are the negative and positive symmetrical components, respectively, which are obtained by the FFT [173] and the Fortescue transform [176].

While, mechanical overload is produced by high torque values outside the nominal operating conditions in the motors, consuming high current levels [156] that cause excessive heating in the stator insulation. Overload can be calculated as the current magnitude that exceeds the nominal value of a motor. In general, the percentage of overload (%OL) is determined as follows:

$$\% \text{ OL} = \frac{I_m}{I_n} \times 100 \tag{3.2}$$

where $I_m$ is the measured current signal and $I_n$ is the nominal current provided by the manufacturer.

### 3.2.2 Motor Protection

In accordance with the standards IEEE Std. C37-96 [159] and NEMA norm [162], an increment of 10°C on the stator temperature deteriorates the insulation system and reduces the motor lifetime by one half. In this regard, a set of thermal limits in which the insulation system is in safe conditions has to be taken into account. These thermal limits can be used according to the standard C37.96 of IEEE [159] to determine alarms and trip thresholds for excessive temperatures in stator and rotor and, thus, protect the motor.

Although motors can tolerate high currents, e.g., during the start-up where high current levels ranging from four to more times of its nominal current value are present [159], the temperature increment of stator winding for a long time may exceed the capability of the insulation system. Therefore, time-outs must be incorporated to provide protection against conditions that generate thermal increments, disconnecting the motor before generating damages into the insulation system.

For mechanical overloads, the time-outs are provided by the manufacturer in form of time-current curves [177]. From the time-current curve provided in [178], the curve is constructed in this work using Matlab software from a set of points extracted manually. This curve represents the permissible time levels at which the motor can operate under an overload condition without exceeding its thermal limit in the insulation system; e.g., for a current of three times the rated current, which represents a value of overload equal to 300%, the motor can safely run at a maximum time of approximately 100 s. Information related to the standard procedures for representation of thermal limit curves is presented in the norm IEEE std. 620 [177]. From the aforementioned, it is evident that the thermal behavior of a motor plays an important role in the design and development of protection schemes.

A motor thermal model can be described by a first-order differential equation as shown in Eq. (3.3), considering the motor as a homogeneous body when it is heated by an electric current [179]. In this model, the difference between the power supplied to the motor and the thermal losses is equal to the product of the thermal capacity of the system and the motor temperature increment [180]. Therefore, it is given by:

$$I^2R - \frac{\theta}{R_T} = MC_s \frac{d\theta}{dt} \tag{3.3}$$

Where,

$I^2R$ represents the losses in motor, θ represents the temperature of the motor, $\frac{\theta}{R_T}$ represents the thermal losses, $MC_s$ represents the system thermal capacity, and dθ/dt represents the temperature rise in motor in time dt.

It is important to mention that there are different types of losses that contribute to the increment of the residual heat emission in the motor, e.g. the iron losses. These losses are due to different electromagnetic phenomena that arise in the stator, such as the hysteresis and eddy currents. These phenomena together with voltage unbalance effects on the positive and negative sequence components produce an opposite motor rotation [181-182]. As there are different sources and causes of losses, they are not directly taken into account in Eq. (3.3). In order to provide time-protection models for overload and voltage unbalance conditions, which have similar mathematical forms but with different variables and values in their coefficients, the motor is treated as a homogeneous body. Nevertheless, since voltage unbalances directly affect the heating in the stator windings and considering that this negative effect is one of the main factors that degrade the motor insulation life, the motor thermal model defined by (3.3) can be used for modeling the motor thermal performance.

From (3.3), the mathematical expression of the time $t$ required to reach the maximum temperature as a function of the motor current $I$ is [177, 178]:

$$t = \tau \ln\left(\frac{I-I_P}{I-{I_{sf}}^2}\right) \qquad (3.4)$$

Where,

$\tau$ is the thermal time constant that represents the product of the thermal resistivity, $R_T$, and the thermal capacity $MC_s$. $I_P$ is the operation current and $I_{sf}$ is the current at the service factor. Eq. (3.4) provides the time-out in which the motor must be disconnected [183].

It should be pointed out that the time-outs are provided for an overload condition but not for a voltage unbalance condition. The generic time-overload model based on Eq. (3.4) results on:

$$t(\%\ OL) = \tau\ ln\left[\frac{(\%OL+100)^2-100^2}{(\%OL+100)^2-(100\ SF)^2}\right] \tag{3.5}$$

And the generic time-unbalance model based on Eq. (3.4) is given by:

$$t(\%\ UN) = \tau\ ln\left[\frac{(\%UN+100)^2-100^2}{(\%UN+100)^2-(100\ SF_{UN})^2}\right] \tag{3.6}$$

**3.3 Motor Protection Schemes**

In order to obtain a protection model for voltage unbalance and mechanical overload, the scheme depicted in Figure 3.1 is proposed. Firstly, the induction motor was operated under normal operating conditions, which includes pseudo voltage unbalance, balanced supply voltage, slightly mechanical underloading and rated mechanical loading. As expected, corresponding cut-off time was infinite and the motor will remain operating. Later, it was operated under mechanical overloading condition while supply volage was kept balanced and the corresponding cut-off time was calculated, from Eq. (3.5) , hence the switch was turned off in time i.e. cutoff time. Again the motor was operated under rated mechanical overload but unbalanced supply voltage and the same operation was performed as in done in previous condition, cut-off time in this case is calculated by using Eq.(3.6). Then motor was operated under both the abnormal condition, including mechanical overloading and volage unbalance, and cut-off time corresponding to both the conditions were calculated and their severity were compared, and motor was turned off in time.

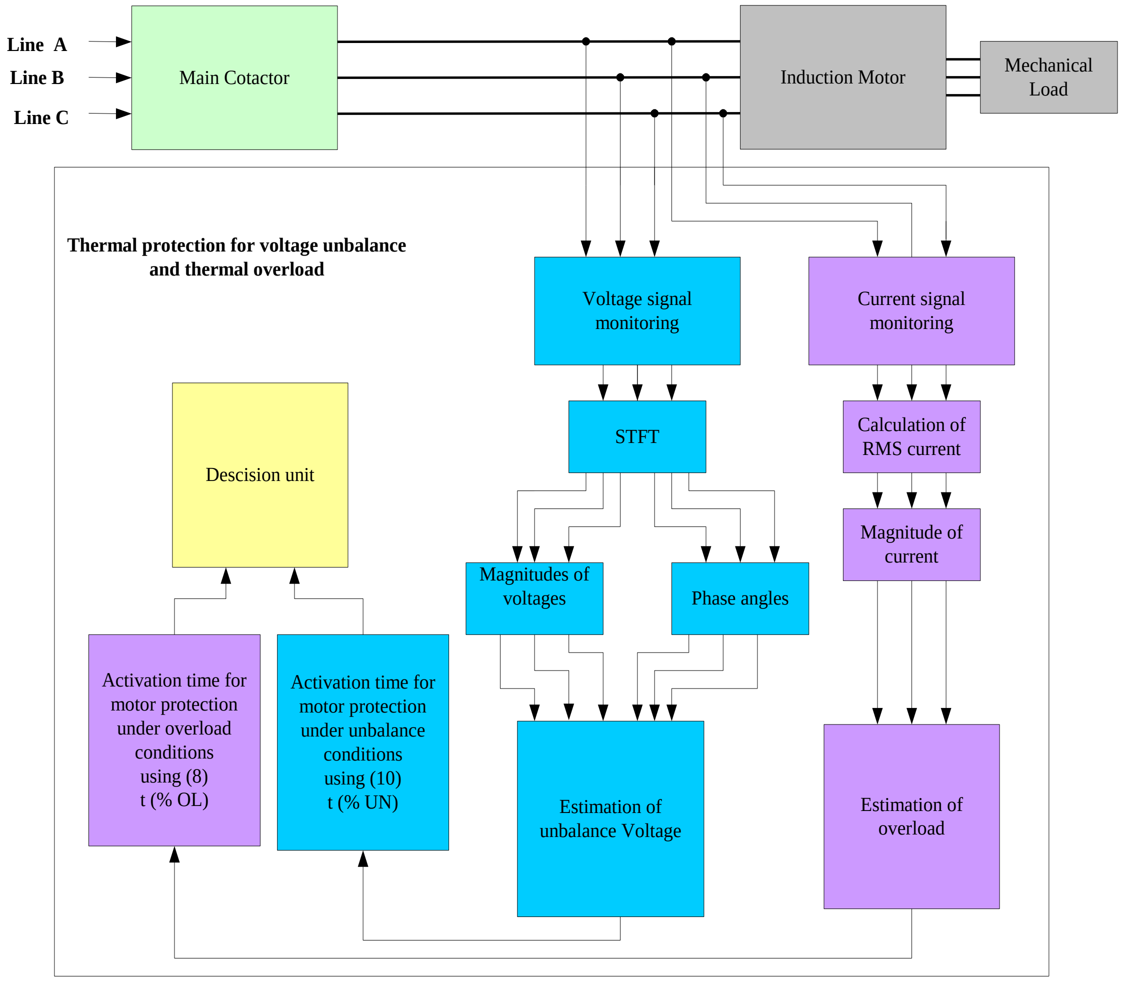


Figure 3.1: Mechanical overload and voltage unbalance protection scheme

Again, motor was operated under slightly modified condition of last condition and it is observed that the increase in voltage unbalance has more severe effect then due to increase in mechanical overloading. The moral of the story is, the retrieved voltage and current signals, which are in time domain, are processed (by using STFT) to get the corresponding phasors. Positive and negative sequence components are calculated from the voltage phasor by using Fortesque theorem. These sequence components are then used to calculate the indicator of (%UN), which will later be used to calculate the corresponding cut-off time, if there any voltage unbalance present. Simultaneously, current signal is also processed and corresponding overload cut-off time has also been calculated, if any. Cut-off time corresponding to both the abnormal operating conditions are compared and the operating time of motor has been decided by the Decision Unit (DU) accordingly. Once the operating time surpasses the cut-off time, a trip signal is generated by the relay and is passed to the switching device to turn off the supply.

### 3.3.1 Modelling of Induction Motor Protection Schemes

The motor protection scheme explained in last section is implemented in MATLAB® SIMULINK® software, where various conditions have been taken into consideration and elaborated briefly.

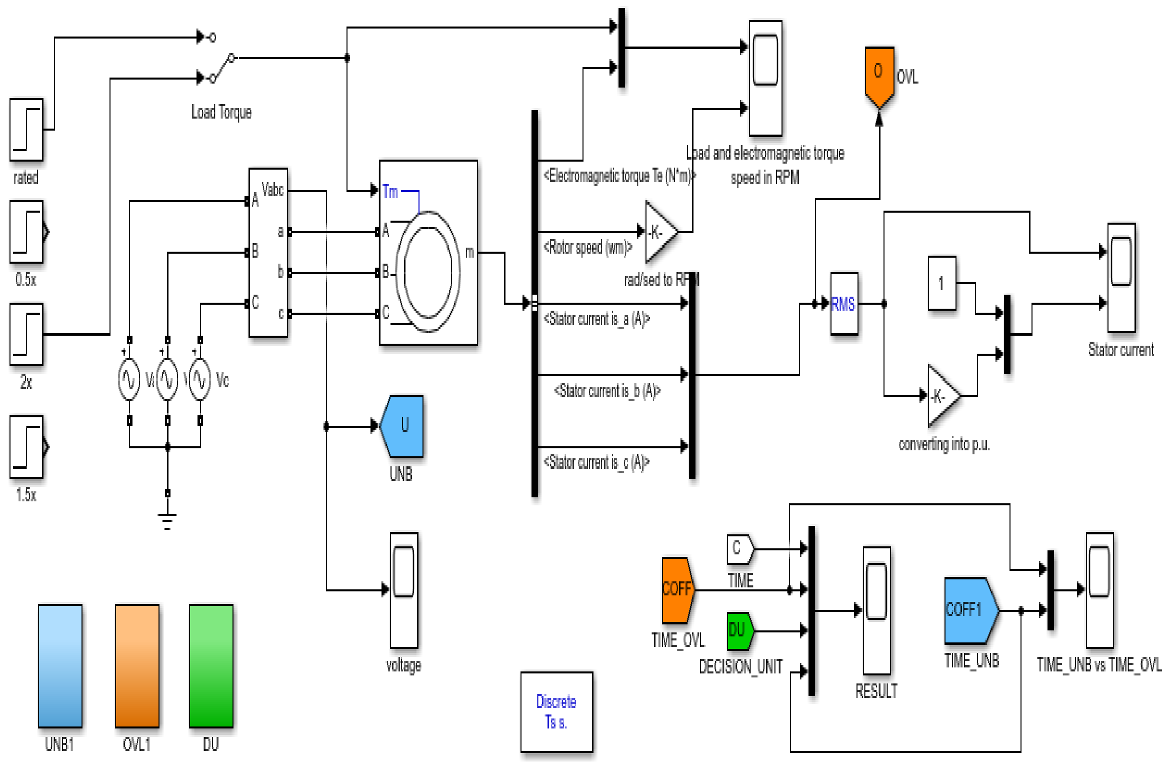


Figure 3.2: Protection scheme for discrimination of overload and voltage unbalance for Induction Motor

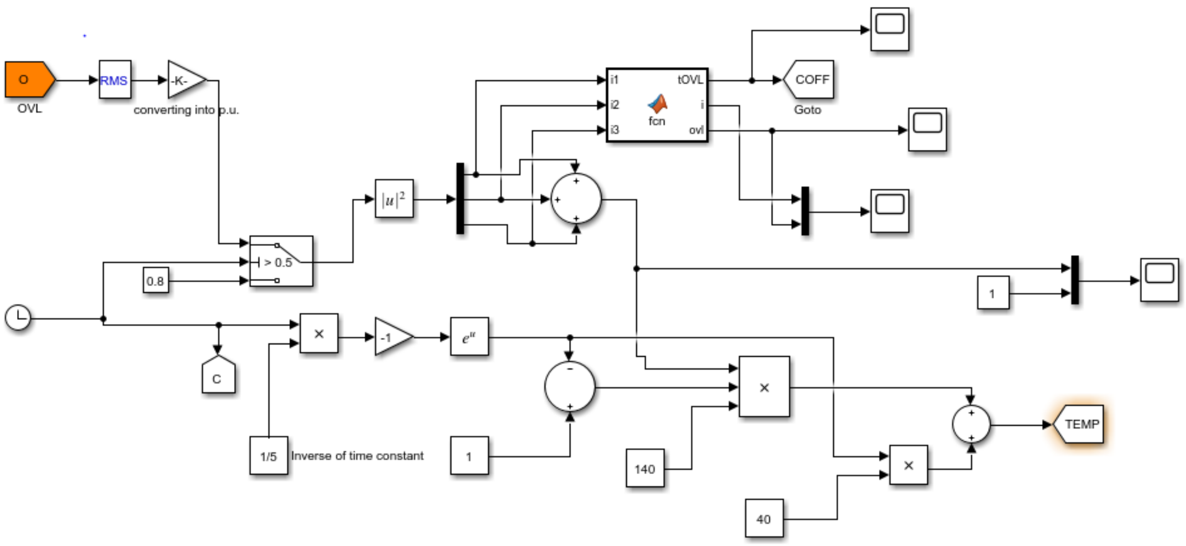


Figure 3.3: Overload block for IM Protection.

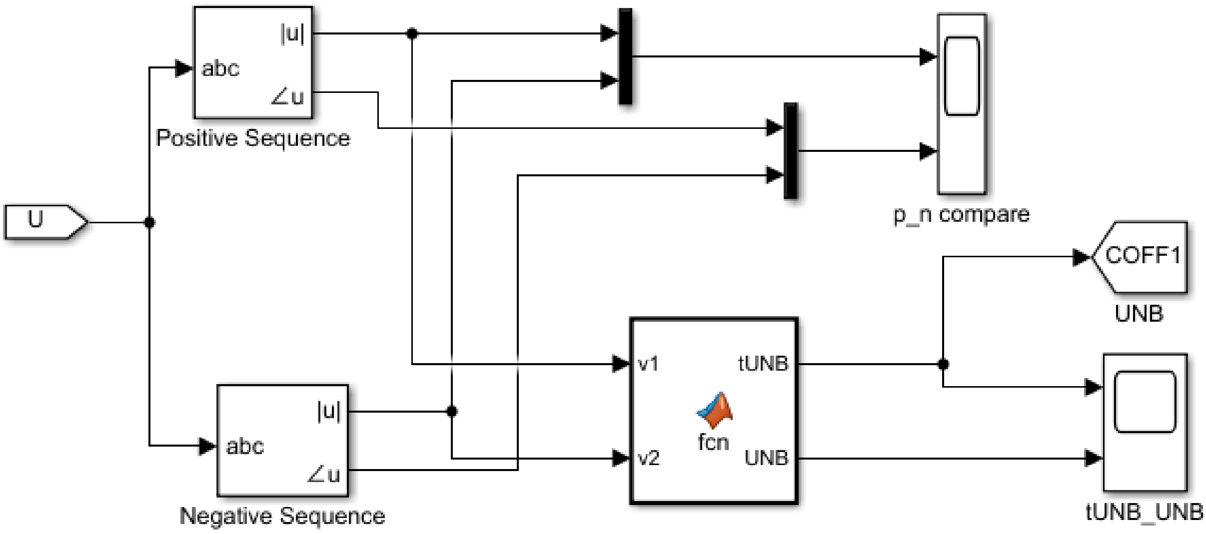


Figure.3.4: Voltage unbalance block for IM protection.

The above protection scheme implementation is demonstrated in Matlab platform with relevant simulink model and associated subsystems as mentioned in Figure 3.3. 3.4 and 3.5. The specification of the motor for above objective is mentioned in Table 3.1.

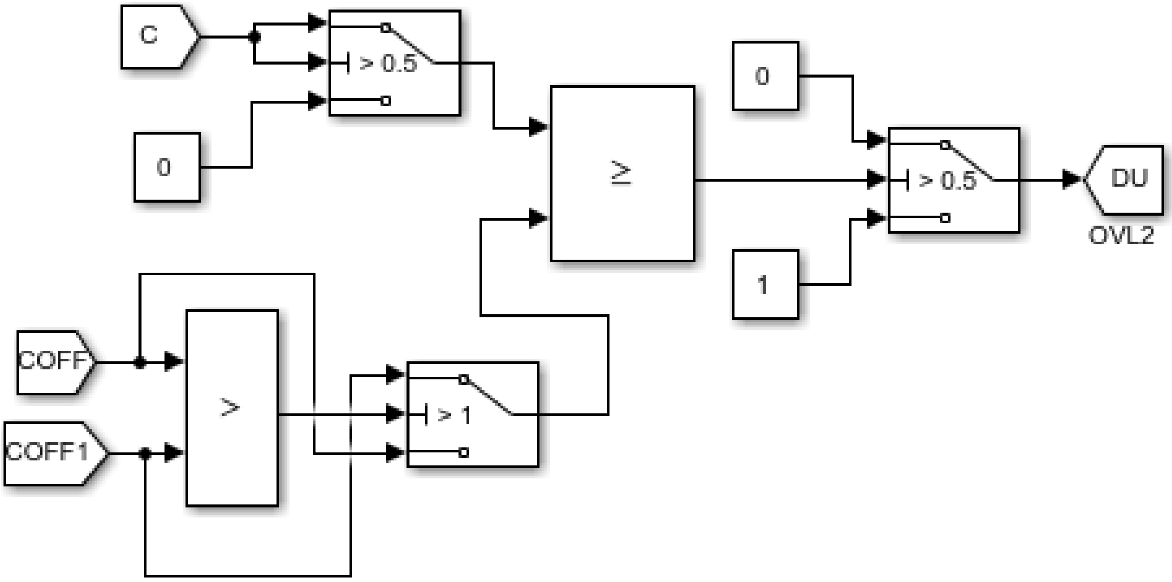


Figure 3.5: Decision unit block for IM Protection

Table 3.1: Motor parameters for protection against overload and voltage unbalance

| Parameters | Values |
|---|---|
| Power | 4 kW |
| Voltage Rating | 400 V |
| Frequency | 50 Hz |
| Rated Speed | 1440 rpm |
| Service Factor for Over Load (*SF*) | 1.15 |
| Service Factor for Unbalance ($SF_{UN}$) | 1.08 |

The various case studies has been studied in this section under different mechanical overload and voltage unbalance conditions.

In figures, from Fig.3.6 to Fig 3.10, x-axis represents "Time" while y-axis represents numerical values that could be either "Time" or "Logic (0 and 1)" or "calculated cutoff time of the thermal relay (corresponding to abnormal operating conditions like mechanical overloading and unbalanced supply voltage)", if any, depending upon the legend shown in the figures, which are **RED, BLUE**, **GREEN** and **YELLOW**.

**RED** curve indicates switching action of the contactor with time where 1 corresponds to logic-1, means switch is closed and 0 corresponds to logic- 0, means switch is open.

**BLUE** curve indicates calculated cutoff time of the thermal relay corresponding to overloading, if any, or the corresponding cutoff time will be large under normal operating condition and contactor will remain closed for a considerable long time.

**GREEN** curve indicates calculated cutoff time of the thermal relay the corresponding to unbalanced supply voltage, if any, or the corresponding cutoff time will be large under normal operating condition and contactor will remain closed for a considerable long time.

**YELLOW** curve simply represents time which is in resemblance to operating time as long as RED curve is at LOGIC-1 i.e. for how long the motor will remain operated. It has been shown just to depict the switching action of the switch once operating time surpasses calculated cutoff time (corresponding to abnormal operating conditions like either mechanical overloading or unbalanced supply voltage or both), if any, since x-axis also represents time. YELLOW curve will always be a straight line with slope 1 since both x-axis and y-axis represent time.

Here cutoff time corresponding to different abnormal operating conditions implicates "for how long it is safe to operate motor".

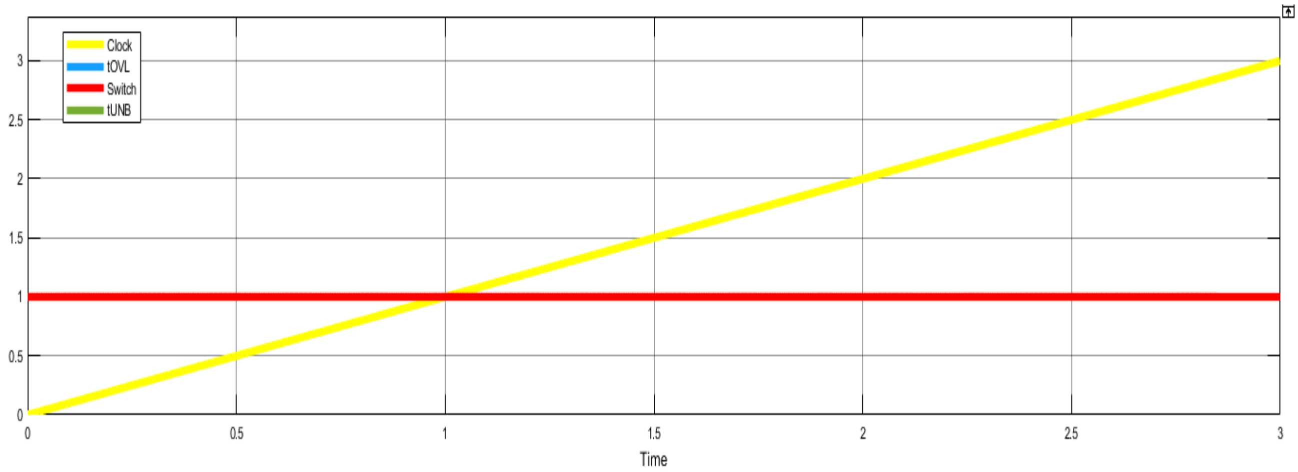


Figure 3.6: Rated mechanical overload and balanced supply voltage (0% UNB)

The Figure 3.6 indicates RED curve remain at logic 1 for the considered time on x-axis hence the contactor will continue to remain ON.

Since no BLUE curve is present which implicates cutoff time (tOVL) corresponding to overloading is considerably large since the motor would operate either under rated or slightly under-rated condition.

Since no GREEN curve is present which implicates cutoff time (tUNBL) corresponding to unbalanced supply voltage is considerably large since the motor would operate either under balanced supply voltage or pseudo balance condition with permissible limit of 5%.

The YELLOW curve is present as usual, which is straight line with slope 1 for the considered time on x-axis.

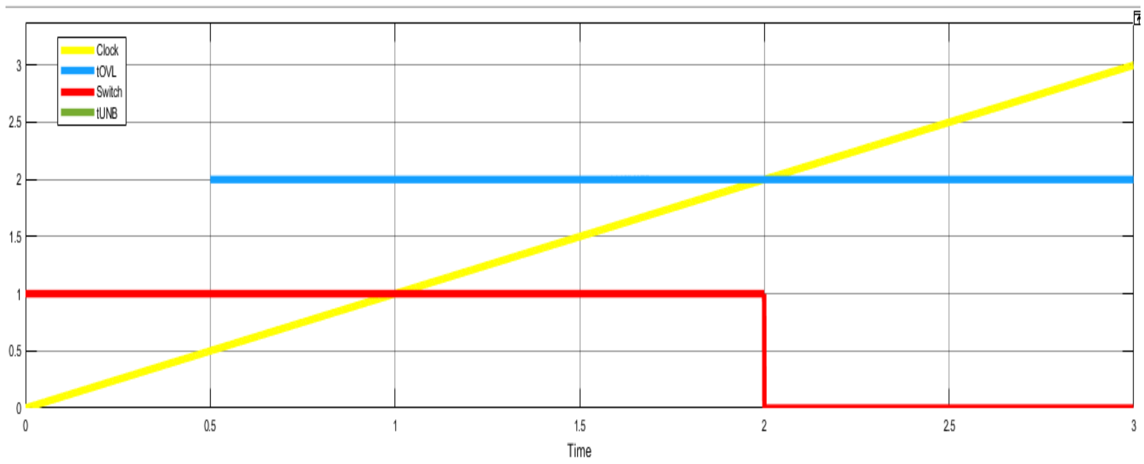


Figure 3.7: Mechanical overloading and balanced supply voltage (0%UNB)

The Figure 3.7 indicates there is an additional overload factor since BLUE curve is present, in which contactor is turned off at appropriate time as RED curves goes from LOGIC-1 to LOGIC-0, which indicates the case of overload.

The RED curve goes from LOGIC-1 to LOGIC-0 (means contactor is turned off) as long as operating time, value on YELLOW curve, surpasses the value of BLUE curve.

Since no GREEN curve is present which implicates cutoff time (tUNBL) corresponding to unbalanced supply voltage is infinite since the motor would operate either under balanced supply voltage or pseudo balance condition with permissible limit of 5%.

The YELLOW curve is present as usual, which is straight line with slope 1 for the considered time on x-axis.

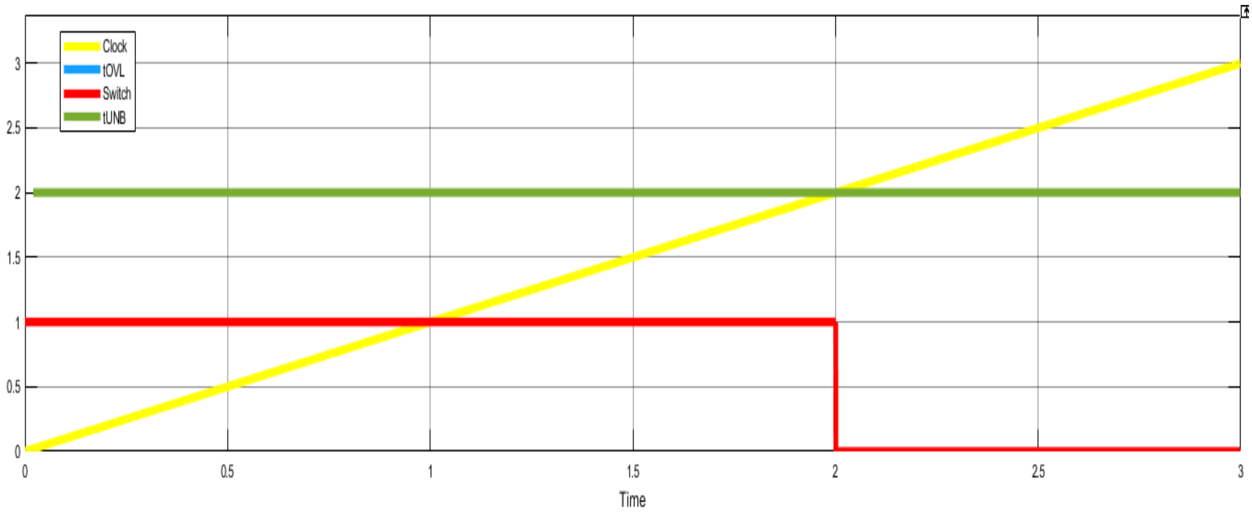


Figure 3.8: Rated mechanical and balanced supply voltage (6.25 % UNB)

The figure 3.8 indicates the unbalanced supply voltage which is deliberately created in permissible range, which is 5-18%, since GREEN curve is present.

The RED curve goes from LOGIC-1 to LOGIC-0, means contactor is turned off, as soon as operating time (values on YELLOW curve) surpasses the value of GREEN curve.

Since no BLUE curve is present which implicates cutoff time (tOVL) corresponding to overloading is infinite since the motor would operate either under rated or slightly under-rated condition.

The YELLOW curve is present as usual, which is straight line with slope 1 for the considered time on x-axis.

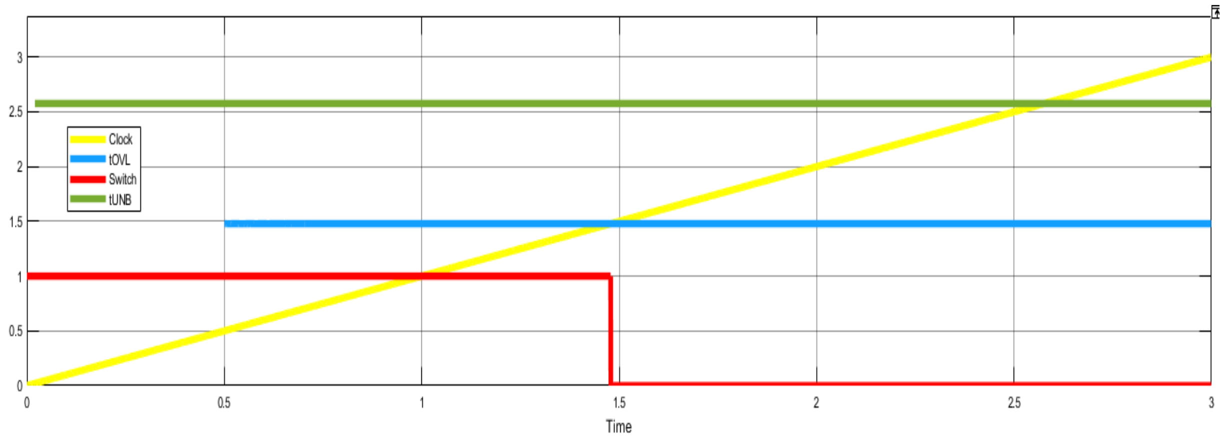


Figure 3.9: Mechanical overload (70%) and balanced supply voltage (6.7 % UNB)

The figure 3.9 has both BLUE and GREEN colored curves hence indicate the simultaneous consideration of both mechanical overload and unbalanced supply voltage followed by the proper switching action.

Since the value of calculated cutoff time of thermal relay corresponding to mechanical overload (which is tOVL at OVL=70%) is lesser than that of unbalanced supply voltage (which is tUNB at UNB=6.7%) hence it can be concluded that in this case heating effect of mechanical overloading is more prominent than that of unbalanced supply voltage.

The RED curve goes from LOGIC-1 to LOGIC-0, means turned off, as soon as operating time (values on YELLOW curve) surpasses the value of BLUE curve.

The YELLOW curve is present as usual, which is straight line with slope 1 for the considered time on x-axis.

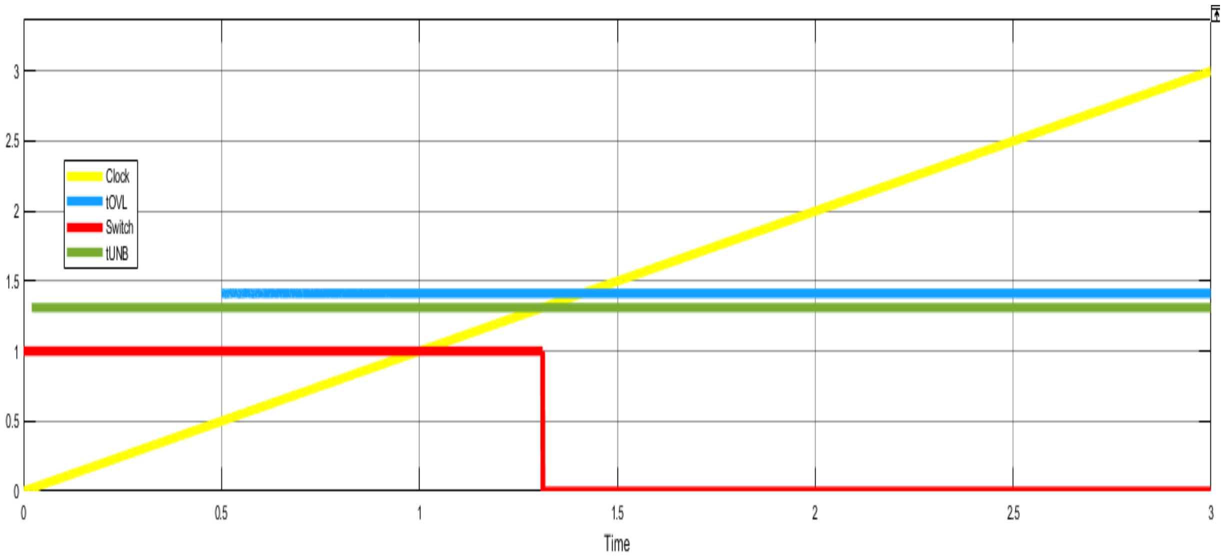


Figure 3.10: Mechanical overload (80%) and balanced supply voltage (14.01 % UNB)

The figure 3.10 has both BLUE and GREEN colored curves hence indicates the simultaneous consideration of both mechanical overload and unbalanced supply voltage followed by proper switching action.

Since the value of calculated cutoff time of thermal relay corresponding to mechanical overload (which is tOVL at OVL=80%) is greater than that of unbalanced supply voltage (which is tUNB at UNB=14.01%) hence it can be concluded that heating effect is more pronounced in the voltage unbalanced due to manifestation of negative sequence of voltage in comparison to overload.

The RED curve goes from LOGIC-1 to LOGIC-0, means contactor is turned off, as soon as operating time (values on YELLOW curve) surpasses the value of GREEN curve.

The YELLOW curve is present as usual, which is straight line with slope 1 for the considered time on x-axis.

### 3.3.2 Short-Time Fourier Transform (STFT)

The Short-Time Fourier Transform (STFT), is a Fourier-related transform used to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time**.** In practice, the procedure for computing STFTs is to divide a longer time signal into shorter segments of equal length and then compute the Fourier transform separately on each shorter segment. This reveals the Fourier spectrum on each shorter segment. One then usually plots the changing spectra as a function of time [184]. The behavior of the real-world signals (which are predominantly non-stationary) could be observed in fullness by time-frequency (TF) representation into the time-frequency domain (TFD), providing information for both the time and frequency localization of the signal. Moreover, one might be interested in performing modifications into the TFD (*e.g.*, a time-varying thresholding) and then resynthesizing of the modified signal. In case of the voltage signal, it is processed through Short-time Fourier Transform (STFT) to get the corresponding phasors. STFT has more significant analysis on non-stationary signal that changes with time for evaluation of amplitude and phase. The STFT adds a time dimension to the base function parameters by multiplying the infinitely long complex exponential with a window to localize it. The actual trade-off between time and frequency is determined by the choice of the window function [185]. In signal processing, a window is basically a mathematical function that is zero-values outside of some chosen interval, normally symmetric around the middle of the interval, usually near a maximum in the middle, and usually tapering away from the middle. Mathematically, when another function or waveform/data sequence i.e. current and voltage signals in this case is multiplied by a window function the product of two is also zero-valued outside the interval being chosen. All that is left is the part where they overlap, the "view through the window". Equivalently, and in actual practice, the segment of data within the window is first isolate, and then only that data is multiplied by the window function values. The reason for examining segments of a longer function includes detection of transient events and time-averaging of frequency spectra. The duration of the segments is determined in each application by requirements like time and frequency resolution. But that method also changes the frequency content of the signal by an effect called spectral leakage. Each window function is characterised by corresponding mathematical expression and shape (like main and side lobe). There are various windows that have been taken into consideration like Blackman window, Hann window, Hamming window etc. The limits of UNB(%) are set in between 5% to 18%. From the model developed, it has also been observed that infinite cut-off time is obtained under balanced supply voltage, UNB(%) below 5%, rated load and below rated load, hence motor will remain ON under such operating conditions.

### 3.3.3 Characteristics of the Blackman Window for STFT analysis

The performance of the STFT corresponding to Blackman Window in context of evaluation of amplitude is shown in the given subplots. These figures indicates the filtered fundamental components corresponding to all three phases(in case of balanced as well as unbalanced supply voltage), which is 50Hz in this case,  These phasor are later used to calculate the negative and positive sequence components which are used to calculate UNB(%).

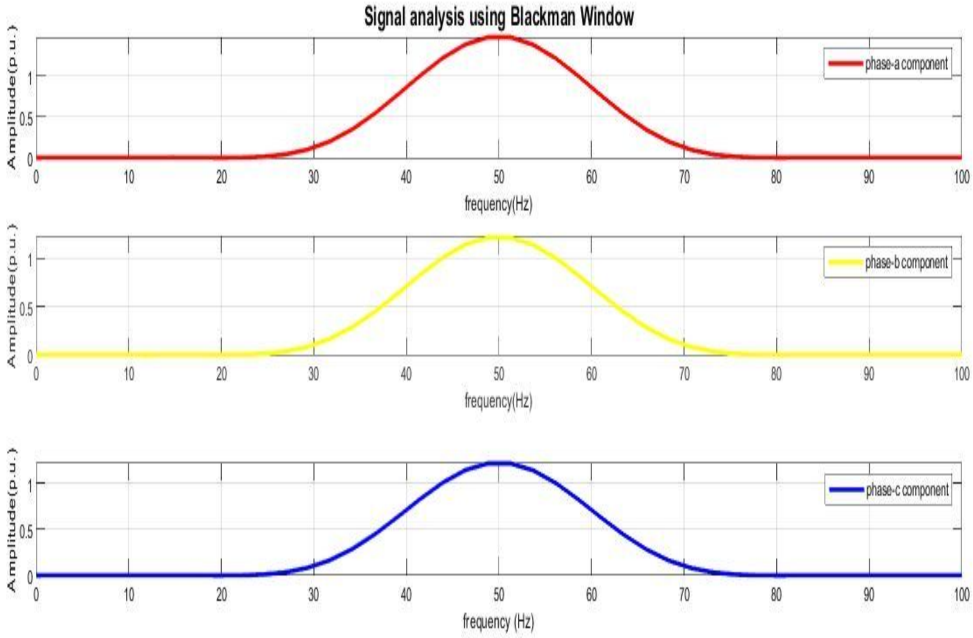


Figure 3.11: Signal analysis by STFT using Blackman window

### 3.4 Result and Discussion

The voltage and current signals are retrieved from the sensors at a sampling rate $2.5 \times 10^{-5}$ Hz. After the sampled data is obtained it is processed with STFT in order to get the magnitude and phase of the signal finally for the discrimination between voltage unbalance and overload as mentioned in Eq. (3.1) and Eq. (3.2) respectively with additional service factor being considered for accurate discrimination of these two disturbances. As the sequence analyser is a key indicator to obtain negative sequence component which has been carried by processing the voltage signal with sequence analyser block. Fortesque's theorem is applied to convert the phasor variables to positive and negative sequence components. The amplitude obtained by short time Fourier transform is mentioned in Figure 3.11 which reflects its performance.

## 3.5 Conclusion

The protection scheme as discussed in this chapter explores the advantage of signal processing algorithm which is the correct indicator of discrimination of voltage unbalance and overload. The sequential procedure adopted for the protection scheme is illustrated with detailed operation of contactor switch in case of any disturbance that occurs. The case study with its comprehensive analysis clearly indicates the efficacy of the scheme being proposed. Further inter-turn fault which as important and probable cause of failure in induction motor is discussed by its detailed modelling followed by the corresponding analysis in chapter 4.