Protection of Motors Fed Through ASD

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***Abstract* – In addition to controlling the voltage and current input signals, modern adjustable speed drives (ASD) or variable frequency drives (VFDs) also provide some motor protection functions. However, they fail to provide a biased thermal overload protection (BTP) that must reflect the motor heating due to overload, change in the ambient temperature, loss of cooling, etc. A separate motor protection (SMP) relay is usually used to provide a complete protection and monitoring solution. However, various challenges are associated with the SMP when applied to protect a motor driven by ASD. These challenges are significant distortion in the motor input signals, motor starting/running with continuous varying frequency resulting in varying fan cooling, limitations to motor differential and short circuit protection, allocation of instrument transformers, etc.**
This paper discusses these practical challenges and proposes various solutions to achieve a more accurate, biased thermal protection solution. Also, various general applications of motor protection relay with ASDs are also discussed.

***Index Terms*--Biased Thermal Protection (BTP), Motor Protection, Thermal Protection, Pulse Width Modulation (PWM), Resistance Temperature Detector (RTD), Adjustable Speed Drive (ASD)**

I. INTRODUCTION

Motor protection is a well-established principle. A primary failure indicator for motors is heat, which can damage insulation, bearings, frame, rotor, etc. Once this thermal damage occurs, it is a matter of time until the failure reveals itself as a phase to ground or phase to phase fault, bearing failure leading to rotor impact of the stator, etc. If proper thermal protection is not provided, protection elements such as 50/51 phase and ground and 87 differential protection are used to clear faults resulting from this damage; up till then it is too late; these protection elements are just trying to limit the extent of the damage at that point.

Early analog/mechanical motor protection devices used a theoretical model that responded to measured motor currents to approximate the heat produced in a motor. Temperature measuring devices (TMD) have evolved over time to accurately measure stator temperature to provide a final trip point to protect the motor. The common examples of temperature measuring devices are transducers, thermistors, thermocouples, and resistance temperature detectors (RTDs). RTDs are the most common, as they produce a linear representation of temperature vs. devices like thermistors that avalanche at a defined temperature and which are basically a switch, on or off. For instance, RTDs provide a final absolute trip but is still not sufficient to adequately protect the motor, as RTDs, while giving accurate temp readings, are very slow in response [1]. Due to this slow response time, RTDs should not be used as a primary protection element even though heat is the primary influence factor in motor damage. By the time the RTD reaches the trip temperature, the winding insulation has exceeded the limits.

Because of RTD slow response, algorithms in dedicated motor protection relays have been developed to "bias" the current based theoretical model with the measured stator temperatures during normal operation. RTD biasing corrects the current-based thermal model and place the programmed motor damage curve at the proper point, so as to always reflect the exact state of the motor thermal profile. In this manner, the relay properly protects the motor when an overload occurs.

Current-based thermal model with RTD biasing is an accepted standard motor protection practice and is not disputed in the industry anymore. It is important to remember that the purpose of the modern digital protection relay is not only to protect the driven equipment but to monitor it closely and ensure against premature or false shutdowns. The idea being that over-protection can be as bad or worse than under-protecting a piece of electrical apparatus when it comes to the loss of production and therefore economic costs. Loss of process can cost far more than the loss of a motor. The “art” is to protect the equipment while maintaining the process as long as possible.

Problems with the settings are common, stemming mainly from misunderstandings of what the purpose is in setting these devices, something that varies greatly depending on the customer, application, industry, and protection philosophy.

This agreement on what defines proper motor protection changes when an ASD controls the motor. ASDs are becoming more common due to energy savings and control requirements for better process control and reduced mechanical maintenance of the driven equipment. Modern ASDs are microprocessor-based devices just like modern protection relays, controlling voltage or current, and as such can perform a variety of functions including some motor protection functions. Integrated ASD protection can provide adequate short-circuit protection on the source and load side of the ASD, output under/over voltage and unbalance but the level of protection available in the ASD must be reviewed to determine if it is adequate for the value of the equipment it is protecting. However, ASD does not provide biased thermal protection, winding turn-turn fault protection, sensitive ground fault protection, etc. Moreover, modern motor protection relays provide a complete solution to monitor and diagnose health of the asset, which ASD lacks to provide. Therefore, a separate motor protection relay should be used to provide a complete protection, control, and monitoring solution, especially as the value of the protected equipment rises.

Various challenges are associated with the motor protection when applied to protect motor driven by an ASD. These challenges are: significant distortion in the motor input signals, motor running with continuous varying frequency resulting in varying fan cooling and iron losses. The conventional ASD thermal model is based on the currents and therefore may not properly reflect the motor temperature due to the varying fan cooling, iron losses and harmonics.

This paper, previously presented in a conference [8], proposes solutions to these challenges in order to achieve an accurate thermal model such that it properly reflects these influences. Section II reviews typical ASD motor protection to properly understand the need for external motor protection. Section III provides more details of the challenges associated with motor protection when applied to a ASD driven motor and proposes solutions to these problems. General applications of motor protection relays with ASDs are discussed in section IV.

II. ASD DRIVEN MOTOR PROTECTION

References [2] and [3] discuss typical protection included in the ASDs. These protection elements are further categorized into source side (zone 1) and load side (zone 2 & 3) protections, presence dependent on ASD topology, as shown in Fig. 1.

Source side protection may include: the short circuit overcurrent protection (50/51), overload (49), under/overvoltage (27/59), under frequency (81U), and transformer differential (87). Load side protection may include: reverse phase sequence (47), under/overvoltage (27/59), voltage/current unbalance (46), over frequency (81O), and motor differential (87).

Modern ASDs have a theoretical motor model that responds to the measured motor currents, integrating current over time similar to early motor protection devices or even modern intelligent electronic devices (IEDs) with advanced features disabled.

All ASD vendors also provide optional RTD input modules to provide final discrete temperature trip protection, but as noted, this level of protection is not considered adequate in non-ASD applications. No ASDs currently use a proper temperature "biased" thermal model to accurately measure and adjust the motor thermal capacity on a continuous basis as multifunction motor protection relays do.

In addition to integrated ASD motor protection, separate motor protection may be required to provide proper monitoring and protection against the overheating due to running overload, extra heating due to unbalance in the phase voltages, mechanical jam, sensitive ground faults, etc. The ASD actively controls the output signals seen by the motor and so inherently can provide many of these functions, but protection is a secondary function to the ASD’s primary purpose and violates some protection philosophies that protection and control should be separate, where possible.

Modern motor protection relay may include: reverse phase sequence (47), under/over voltage (27/59), voltage/current unbalance (46), over frequency (81O), thermal protection (49), phase differential (87), bearing temperature detection (38), jogging protection (66), RTD biasing, mechanical jam (50J), acceleration time, and loss of load (under current/under power) (37).

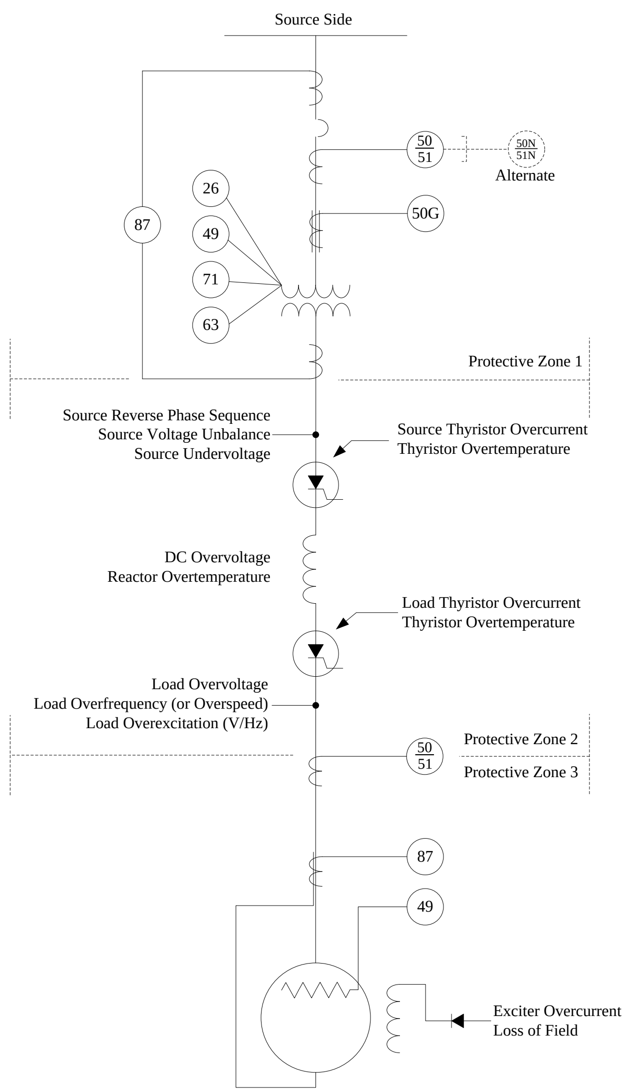

Fig. 1 Typical ASD protection [2]

III. CHALLENGES & SOLUTIONS

This section discusses the aforementioned challenges associated with motor protection when applied to an ASD driven motor application.

Current based thermal protection can fail to determine the exact heating replica when the motor is driven by an ASD. Motor thermal calculations must consider extra heat generated by the ASD waveform, or reduction of the amount of heat removed in the ASD driven motors with shaft driven cooling fan, especially if the application is constant torque. The sources of extra heating in the ASD driven motor are discussed in the remaining part of this section.

a) Motors driven by ASDs can have significant harmonic contents in the input signals. Harmonics in the input signals cause additional copper and iron losses in the stator and rotor. Harmonic currents flow in the motor stator and rotor and therefore produce heat. Overheating results in a decrease in the overall life of the motor. Motor protection relays must operate on the measured true RMS current, due to the non-sinusoidal nature of the ASD output signals. Even the best ASDs produce some harmonic distortion. Relays that extract and operate on the fundamental frequency cannot produce an accurate representation of the thermal influence, a factor that worsens as the ASD topology becomes more rudimentary.

For example, a standard three phase "2 level" PWM ASD produces the highest amount of harmonic effect, (along with higher dv/dt and reflected wave phenomena, neither of which a motor protection relay can have any influence on as that is related to motor insulation design levels and is outside of the scope of this paper). The larger the numbers of "steps" or "levels" in the output waveform, the smaller the individual steps are, and the faster the PWM switches, the more sinusoidal the motor current is and the less impact it has on the motor thermal capacity. Some ASDs may require some form of output filter to reduce these effects further.

Fig. 2a & Fig. 2b show three phase voltages and currents profiles, respectively, for the motor input signals fed from a 2 level PWM ASD with switching frequency of 16 kHz. PWM switching frequency is usually in the range 500–20 kHz [4]. Voltages are much distorted as compared to currents signal, as shown in Fig. 2. Since the switching frequency is very high, the low order harmonic contents in the current signals can be below 10% of the fundamental frequency component, as shown in Fig. 3.

Since currents are measured at the motor side (load side) of the ASD, RMS currents are used in the motor protection relay for the protection against short circuit and monitoring of the motor load and overload conditions. However, phase voltages measured at bus side (source side) of the ASD do not reflect the actual motor input voltages. Therefore, it is strongly recommended not to use voltage protection functions like under/overvoltage, frequency measurement, phase reversal, etc., unless these signals are measured at the ASD output. This itself can be problematic as some ASD topologies will not tolerate the addition of output VT's due to their inductance causing issues with the ASD's ability to "see" the motor characteristics. If used the relay needs to utilize a proper frequency tracking methodology to ensure accurate operation.

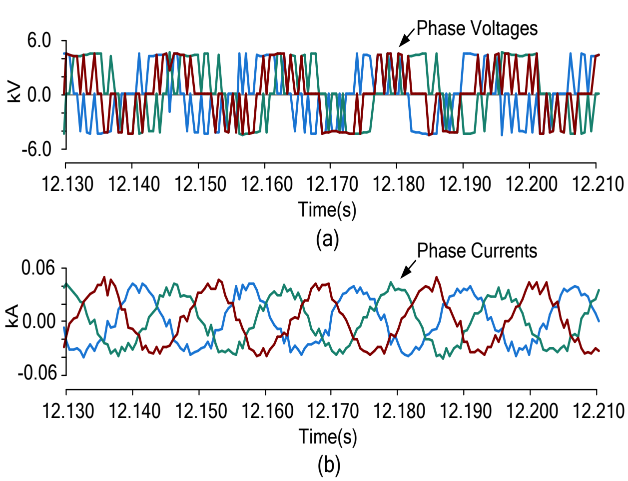

Fig. 2 Three phase motor input signals: (a) voltage; (b) current

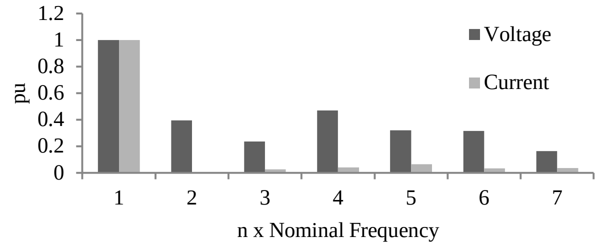

Fig. 3 Harmonic contents in motor input signals

b) In any motor that is not forced cooled, the cooling fan is attached to the motor shaft and cooling of the motor varies with varying frequency or speed of motor. Simple current based thermal protection can fail to calculate the reduced cooling resulting from the varying fan speed since the given motor manufacturer damage curves are based on full speed operation only. Example of a typical damage curves is shown in Fig. 4. For each point on the damage curve a certain amount of cooling effect is assumed to counterweigh the heat that current produces.

Following are two solutions in order to take this extra heating into account by the current based thermal protection.

Solution 1 RTD Biasing [6]: Current based thermal protection can be corrected by measuring the actual temperature of the stator winding. While the ASD is varying speed, RTDs can help to correct the thermal capacity calculated by the thermal model. Fig. 5 shows the graph of thermal capacity calculated using the RTD Bias. However, to

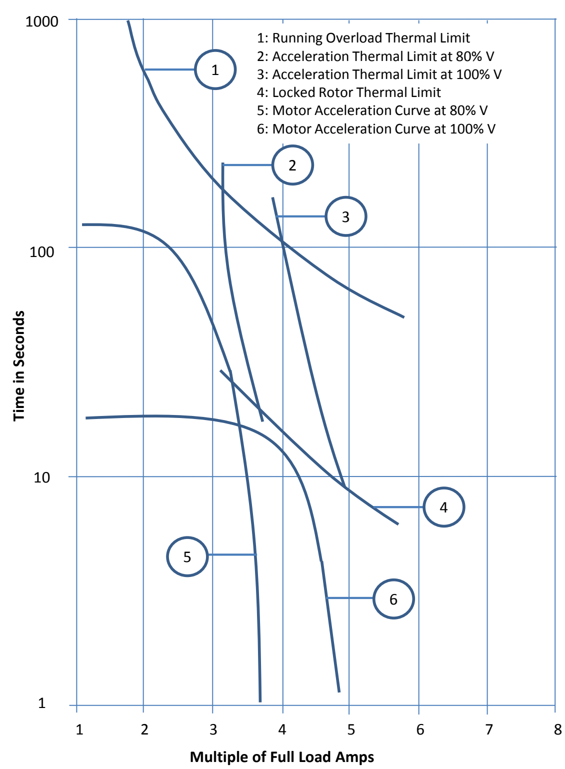

Fig. 4 Typical motor damage curves

properly use the RTD biasing feature it is important to know the ambient temperature, normal running motor temperature, maximum allowable temperature and hot/cold ratio. This information can be easily obtained from the motor nameplate or data sheets. Fig. 5 shows the thermal capacity used (TCU%) as a function of stator temperature for an insulation class F motor (maximum allowable temperature of 155 ^{0}C defined by NEMA MG1) having ambient temperature of 40 ^{0}C and normal running stator temperature of 130 ^{0}C (80 ^{0}C + 400 ^{0}C ambient temperature + 10 ^{0}C margin).

RTD biasing feature takes the maximum of the stator temperatures measured by the RTDs and calculates TCU using the following relations:

TCU calculation for normal running load:

$$TCU_{nor} = (1 - H/C) \times 100\% \quad (1)$$

TCU calculation when the stator temperature is between ambient and normal running temperatures:

$$TCU_{RTD} = \left(\frac{T_{act} - T_{amb}}{T_{nor} - T_{amb}}\right) \times TCU_{nor} \quad (2)$$

TCU calculation when the stator temperature is between normal and maximum allowable temperature:

$$TCU_{RTD} = \left(\frac{T_{act} - T_{nor}}{T_{\max} - T_{nor}}\right) \times (100 - TCU_{nor}) + TCU_{nor} \quad (3)$$

This solution helps to calculate the actual thermal capacity available for all motor conditions.

Solution 2 Frequency (Speed) Biasing: Due to the slow RTD response, or in cases where older or smaller motors may not have RTDs or the existing RTDs may have failed due to various factors (possibly ASD influenced), a new algorithm is developed that estimates the change in temperature as a function of motor speed (frequency). Without measuring the actual stator winding temperature, as a further bias input to the standard thermal model. In the first step, the algorithm estimates the actual temperature of the stator as a function of frequency using the following relations. Fig. 6 shows typical temperature vs. frequency characteristic.

$$T = T_1 e^{-(f - F_{start})/\kappa} - T_2\left(e^{-(f - F_{start})/\kappa} - 1\right) \quad (4)$$

where

T_1	is the measured temperature at the starting frequency.
T_2	is the measured temperature when motor is running at maximum allowable frequency
f	is the desired frequency (speed) level
K	fan cooling factor
F_{start}	ASD driven motor starting frequency

The following example illustrates the working of the proposed method:

From the given motor data [5], one can obtain: *T_1 = 1.38 pu, T_2 = 0.91 pu, F_{start} = 0.2 pu, and F_{max} = 1.2 pu*

Step 1: Calculation of the fan cooling constant, K

It is justified to assume that stator temperature at rated frequency (1 pu) is 1 pu such that *T(f=1pu) = 1pu*

Using the given information in (4), fan cooling factor can be calculated as:

$$\kappa = \frac{-(f - F_{start})}{\ln\left(\frac{T - T_2}{T_1 - T_2}\right)} = \frac{-(1 - 0.2)}{\ln\left(\frac{1 - 0.91}{1.38 - 0.91}\right)} = 0.4839$$

Step 2: Determine the temperature as a function of frequency

Using (4), temperature *T* at 0.8pu speed (for example) equals $T(f = 0.8) = 1.0459\, pu$

In the next step, the algorithm calculates the TCU corresponding to temperature (*T*) using the RTD biasing curve (Fig. 5) to correct the current based thermal algorithm.

Validity of the Proposed Solution Based on Frequency Biasing: The proposed method is further validated with the

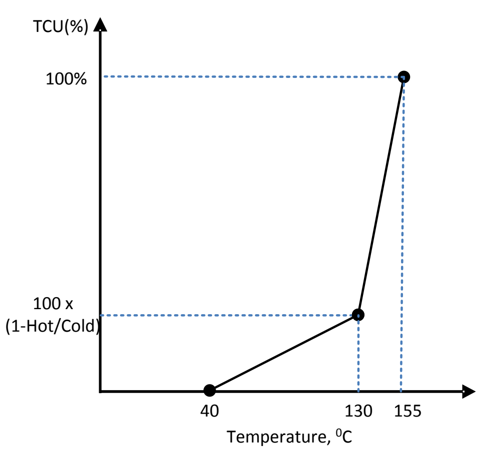

Fig. 5 RTD Biasing

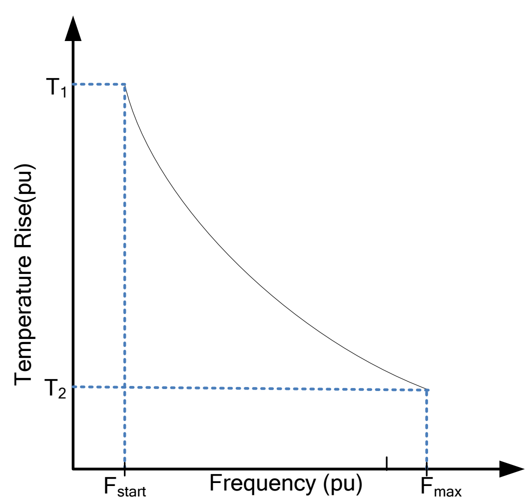

Fig. 6 Temperature vs. frequency

experimental test report data [5]. Fig. 7 shows the accuracy of the proposed method for the estimation of temperature as a function of frequency.

Since standard motor data sheets only provide information on the thermal capability of the motor based on full speed, it is proposed that motor manufacturers should develop tools to properly define the reduction of cooling capability of an ASD driven motor. This will allow easier setting of this new function, rather than the customer attempting to generate test data in the field to allow proper setting, especially for onerous constant torque applications where shaft mounted fan motors are still selected for economic reasons.

IV. GENERAL APPLICATION OF MOTOR PROTECTION RELAYS WITH ASDs

Motor relay CTs should never be connected at the input side of the ASD. The ASD input is transformer/feeder protection, not the motor. The current seen at the input of the ASD at full voltage and frequency bears absolutely no relationship to the current at the motor.

A true 50/51 feeder relay is required for ASD input protection. If it is a smaller ASD and fused contactor is used, care must be taken regarding the instantaneous elements as the fuses must usually be allowed to clear a short circuit.

It is also important to note that the fuses in the ASD input contactor must be "E" type, not "R" type as are used with motors as the characteristics are very different.

Active Front End (AFE) ASDs can contribute fault current from their dc buses to a fault located upstream of the ASD, this contribution should be considered in protection settings and arc flash limit calculations.

It is important to understand the ASD's input protection algorithms, strengths, and weaknesses, where and how it detects faults in order the best set external protection to compliment it and lead to proper ASD protection without unnecessary trips.

Incorrectly set protection devices are one of the largest contributors to loss of production, as previously noted.
ASD motor protection requirements vary depending on the ASD topology. Some ASDs employ an isolation transformer which separates the motor from the power system, in these situations motor relay current based zero sequence ground fault protection may not function due to the ASD output being ungrounded. In these cases, the ASD protects the motor via output voltage monitoring to detect if a phase has gone to ground. These types of ASD can typically continue to run with one output ground fault if the end user desires it.

The same limitation applies to motor differential (87) protection. This is usually applied to large motors and the intention is to pick up the small first fault to ground and trip fast to prevent greater stator damage. However, again, if this is not detectable by current based differential due to the ASD topology then the extra cost of this element (relay, larger motor terminal box and core balance CTs) may not be justified.

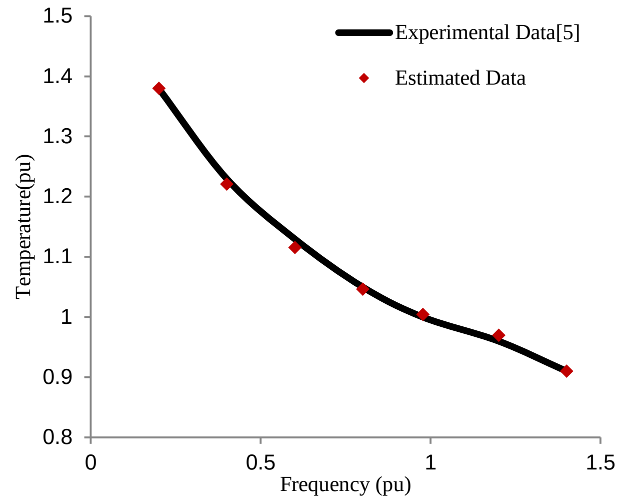

Fig. 7 Validation of the proposed method

Some ASD designs do not include an isolation transformer; these topologies can allow utility short circuit influence to a motor fault and so may require these elements to be applied.
On the same note, the CTs on the output of these types of ASD may be subject to saturation during a motor fault due to this utility contribution passing through the ASD, and so this issue needs to be carefully considered when selecting the CTs.

Moreover, current transformers are normally designed to operate at the nominal system frequency 50Hz or 60Hz. In variable speed drive motor applications having prolonged low-frequency motor operation; this can result in saturation of the CT. Reliable operation of the motor protection relay can be jeopardized with CT saturation happening at low-frequency currents even at low-level currents [7].
This contribution also needs to be considered when calculating arc flash levels.

Testing of the ASD protection algorithms can also be an issue. Typical industrial site commissioning activities usually include validation of all the electrical protection devices, timing and operation. This is standard with protection relays and involves a current/voltage injection test set and a test plan to inject values and record the results to verify operation. Such testing is more problematic with ASDs and can typically only be tested under operational conditions as there is no offline injection testing capabilities. The presence of protection relays allows the protection engineer to feel confident that the apparatus is sufficiently protected from all eventualities.

V. CONCLUSIONS

This paper mainly proposed the solutions to the challenges associated with the biased thermal protection and general application protection functions when applied to the motor driven by an ASD. Challenges like significant distortion in the motor input signals, motor starting/running with continuous varying frequency resulting in varying fan cooling, general protection concepts, and issues are further discussed in more detail.

Two biasing techniques, based on the measurement of temperature and frequency (speed), are proposed. Current based motor thermal protection, when complemented with the proposed biasing techniques, is sufficient to accurately estimate the motor heating generated due to overload, variation in forced cooling with a change in motor speed and change in the ambient temperature. Temperature (RTD) biasing corrects the current based thermal protection by measuring the actual stator temperature. Whereas, frequency biasing helps to correct the thermal protection when RTD slow response is not acceptable or in cases where older or smaller motors may not have RTDs or the existing RTDs may have failed. Frequency biasing algorithm is developed such that it estimates the change of temperature as a function of motor frequency (speed) without measuring the actual stator winding temperature. Frequency biasing algorithm is further validated theoretically with the actual experimental data of the motor that is not forced cooled, and cooling of the motor varies with varying frequency or speed of motor.

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VII. VITA

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