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Development of a Motor Monitoring and Protection Bench Using Digital Relays

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Abstract: This paper presents the development of an educational bench for being used in the teaching of electrical power systems involving: protection, supervision of electrical systems, measurement and acquisition of data. The bench as central elements on SEL digital relays. This article focused on the SEL-849 relay dedicated to the protection and monitoring of electric motors. The protection, monitoring, and measurement functions were used and tested for monitoring and measuring tests of a 0.75Hp induction motor. The tests have how objective to analyze the effects during load operation for two operating conditions, which together with the tests in empty and with the locked rotor, established ambiguous aspects to determine the best operating point. Engine temperature monitoring will also be carried out during tests to survey its thermal curve.

Key words: smart relay, engineering education, education bench for motors tests

1. Introduction

Relays were developed and used since eighteenth century, during the year 1800, when electrical power systems required protection against defects of an electrical nature that occurred in power generation, distribution and communication systems. The first protective relays to be developed and used were those of over current and using electromechanical technology. Electromechanical relays are considered the basis of electrical protection systems. These relays convert electrical energy to mechanical energy by opening or closing electrical contacts.

Thus electromechanical relays (Fig. 1) require various mechanical, magnetic and electrical components to function.

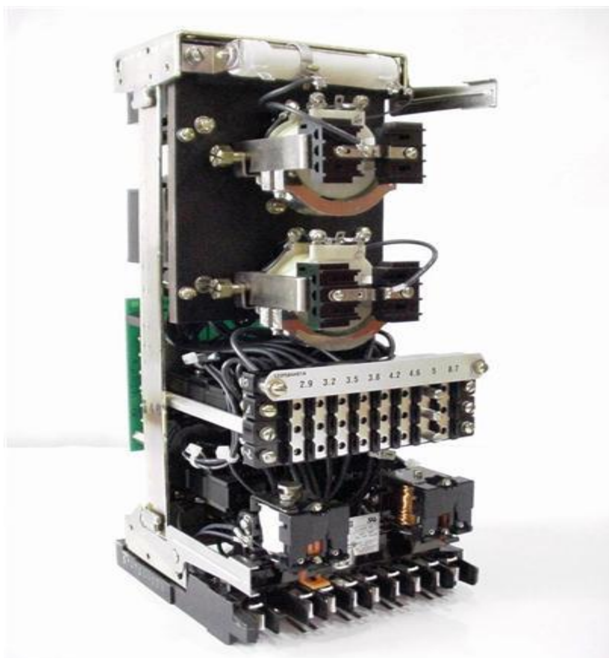

Fig. 1 Differential protection electromechanical relay. Source: courtesy ABB.

Electromagnet coils are the electromagnetic parts and control the opening and closing of the moving relay contacts. The spring-mounted armature is the electromechanical moving part that drives the moving contacts. Also, a set of electrical contacts can be inserted to disarm or arm the protective circuit breakers.

In 1960 comes a new generation of relays, known as solid-state relays, which have the differential of not

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having moving mechanical parts.

Early versions of solid-state relays used discrete devices such as transistors and diodes in conjunction with other electrical devices, however with the development of digital devices, especially microprocessors; it was possible to use linear and digital integrated circuits for processing signal and implementation of logical functions.

Then comes a new relay technology that was introduced to the market during the 1980s, this new generation of digital relays largely replace solid-state and electromechanical. Digital relays operate on circuits considered more straightforward as they contain no moving parts. Digital relays are more accurate and reliable because they use microprocessors that use more accurate numerical counting systems.

Considering the increasing complexity of electrical systems and the development of technology, digital relays are evolving to meet the needs of protection engineers [1]. Fig. 2 illustrates the appearance of a digital relay.

Although digital relays are being widely used in electrical systems by electric utilities and electromechanical replacement industries, there are still systems that use electromechanical relays.

2. Material and Methods

2.1 Cooperation Agreement Between SEL and UNESP /INOVEE

The acronym SEL is short for Schweitzer Engineering Laboratories and is a multinational company dedicated to the protection, control, and automation of electrical systems. SEL produces

Fig. 2 Universal dual current relay of SEL. Source: SEL Relay Catalog [2].

various equipment and software, among them, are relays, which are electrical protection equipment whose application is the protection of loads (motors) against variations of the electrical system; these variations may be over current load, short circuit, unbalance of phases and others.

In October 2014, an agreement was made between SEL and UNESP Campus Guaratinguetá where the company done the donation of some protective equipment for the implementation of a protection and automation laboratory for electrical power systems at the InovEE (Energy Efficiency Innovation Center), Faculty of Engineering campus of Guaratinguetá.

Through this agreement, undergraduate students developing research at InovEE began the study of relays and equipment donated by SEL to conduct research aimed at protecting, automating and acquiring data from electrical power systems.

2.2 Educational Platform

The bench test has the following SEL relays:

- SEL-387 is a relay on current and differential current for the protection, control and measurement transformers and feeder buses. These relays are equipped with three-phase current inputs to implement independent and programmable differential protection of single or dual slope.
- SEL-2516 is a remote rack I/O module suitable for use in substations or industrial control and automation systems, this remote module is equipped with additional monitoring for SEL communications processors with eight external contact inputs and outputs (I/O).
- SEL-3360 is a rugged compact industrial computer for substation, industrial automation and control systems. Eliminating all moving parts (including rotating hard drives and fans) and using error correction code memory technology.

- SEL-849 is an intelligent motor protection relay monitoring the quantities: current, voltage, temperature, electric arc detection and power measurements, providing phasor diagrams of the power systems. It also offers basic motor protection and monitoring functions such as short circuit, pressure drop, locked shaft, frequent starting (overheating) voltage and current imbalances, and phase failure.

2.3 Development of Engine Testing and Monitoring Bench

The studies were initiated by the SEL-849 (Fig. 3) intelligent relay for motor protection and monitoring of electrical quantities and therefore the project was initiated by the study of this relay.

Taking advantage of the characteristics of the relay that measures electrical, thermal and mechanical quantities as RMS values of voltage and current, frequency, power, power factor (FP), thermal and rotation using encoder inserted in the digital inputs.

The assembly was initiated by the electrical connection of the relay, together with the contactor that will perform the motor to start and stop actions, as well as the motor shutdown action in case of failures. Figure 4 illustrates the appearance of the panel with the relay accessory elements, which are push buttons, lamps, auxiliary contacts and circuit breakers.

To simulate the loads on the motor the bench has two types of brakes: a Focault brake and a brake that uses the resistive braking function of the frequency inverters. The bench also has temperature sensors for protection

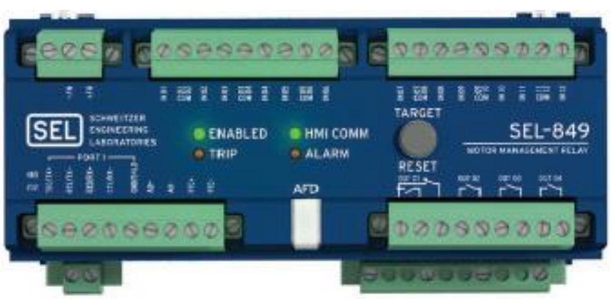

Fig. 3 SEL-849 smart relay for motor protection. Source: SEL Relay Catalog [2].

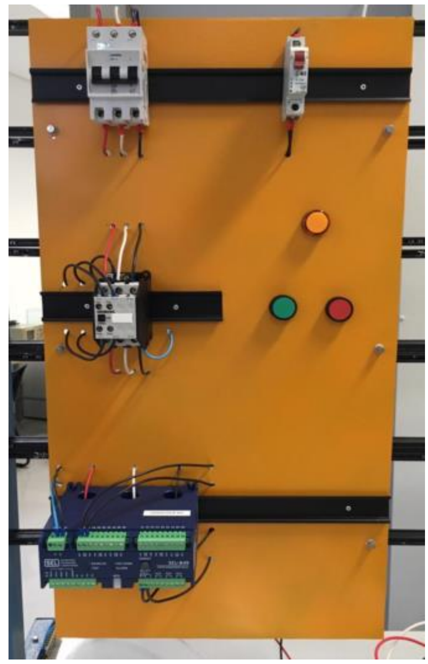

Fig. 4 Appearance of the bench developed for engine testing.

and thermal analysis. Fig. 5 illustrates a block diagram of the bench with its respective elements.

The detailing of the workbench electrical system is illustrated in Fig. 6, the three-wire power diagram shows each of the devices used on the workbench.

Fig. 7 shows the appearance of the complete bench for testing and monitoring the quantities of electric motors and other components of the electrical system.

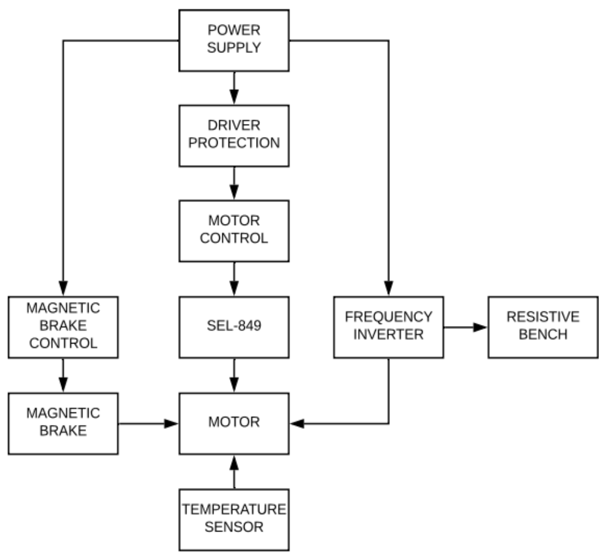

Fig. 5 Developing workbench block diagram for analysis and protection of electrical systems.

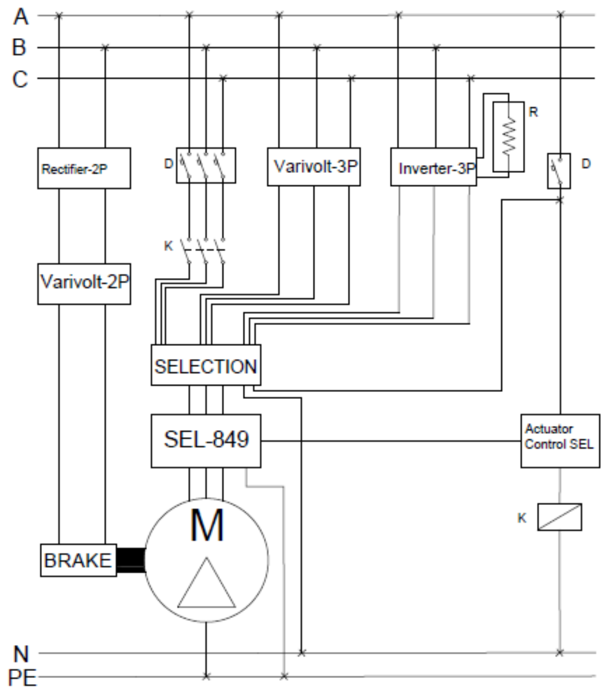

Fig. 6 Three-line diagram illustrating bench components.

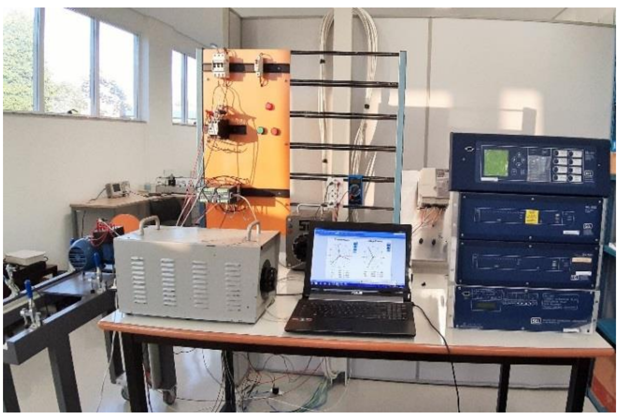

Fig. 7 Developing bench aspect for analysis and protection of electrical systems.

3. Results and Discussion

A 0.75 Hp squirrel cage induction motor, voltages 220/380 V, 1680 rpm, category N was used for the tests. The motor plate is illustrated in Fig. 8.

3.1 Testing SEL-849 Relay Protection, Measurement, and Graphic Functions

Initially, some relay protection functions were observed, such as: over current, phase failure, voltage unbalance, overload and locked axis. The relay still has several other functions such as protection due to

Fig. 8 Motor plate used in the SEL relay bench.

harmonics, arc, over-temperature, and others, and as the workbench is still under development, these functions have not been tested in this work.

The phase failure function has been set to a 5s trip time as well as the minimum voltage value to sensitize the trip relay. The test was performed by removing one of the phases on the relay and waiting for the time to shut down.

The same adjustment was used for voltage unbalance function, and the simulation was performed with the aid of a varivolt where the autotransformer brushes were properly displaced to simulate an unbalance between voltages, and after 5s the relay acted.

The overload was simulated by the electrodynamic brake action set to a condition that imposed an overload value that exceeded the actual overload current settings. The same procedure was performed for the overcurrent function and the relay cut the contactor power used in the motor drive.

The relay also features effective value measurement functions for electrical quantities, voltage, and current phase angles, power factor, harmonic components, indicating the THD and voltage and current unbalance factor.

The relay can also be used as a data acquisition system, and its mass memory can record as many points as possible to plot voltage, current, power or other trend graphs, as shown in Fig. 9.

The current and voltage waveform for the tested motor was obtained for the rated operating condition and illustrated in Fig. 10. Another graphical function of the relay is to be able to plot the phasor diagrams of voltages and currents as shown in Fig. 11. These diagrams allow a view of the operating conditions of the electrical system as well as the load at which the SEL relays are protecting.

3.2 Empty Test

To determine the motor losses for loss and performance analysis under voltage unbalance conditions, the locked-rotor no-load tests were performed. Using the SEL relay data acquisition and measurement functions, the following values for the no-load test were obtained as listed in Table 1.

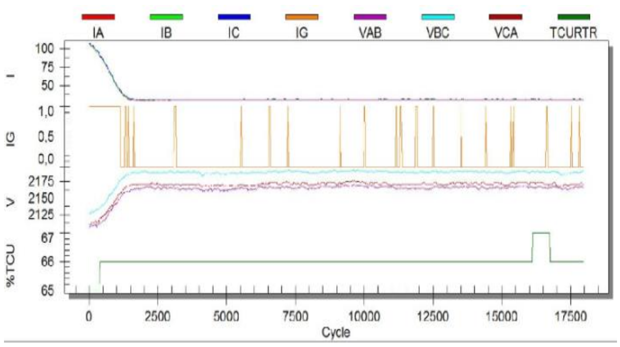

Fig. 9 Trend graph plotted by relay program during motor start.

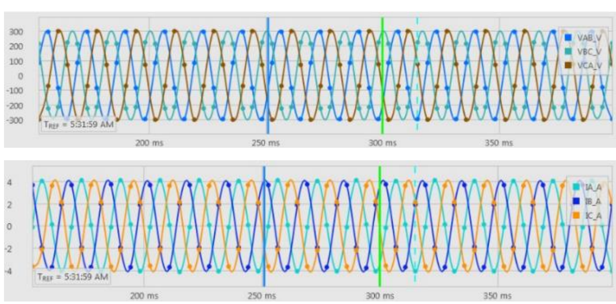

Fig. 10 Graph of voltage and current plotted by the relay program.

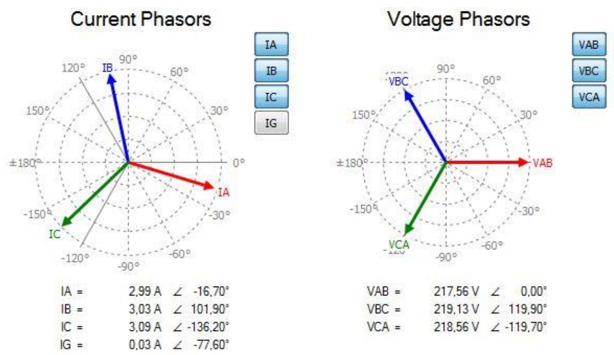

Fig. 11 Voltage and current phasor diagrams plotted by the relay program.

Table 1 No-load data.

No-load current [A]	No-load voltage [V]	No-load power [W]	Rotation [rpm]
3.11	242.23	221	1797
2.45	221.86	151	1797
1.95	201.3	108	1797
1.65	181.18	82	1796
1.41	161.48	66	1795
1.21	141.1	53	1795
1.05	121.76	43	1793
0.87	101.41	34	1790
0.72	81.91	28	1784
0.58	61.18	23	1770
0.51	41.42	20	1719
0.58	20.9	***	***
Operation in the nominal voltage			
2.41	219.8	149	1798

To separate the losses, the current and power versus voltage graphs were plotted, as shown in Fig. 12. In the no-load test, the voltage is reduced from a voltage value of at least 20% above nominal. And the voltage decreases until the current is decreasing again as shown in the graph from 41.42 Volts.

The procedures adopted to determine the losses in the core of stators operating at 60 Hz (or 50 Hz) of sinusoidal power will be IEEE st-432-1992 [3]. Other recommendations follow established in Ref. [4].

For the analysis of the losses, a regression was made in both curves, adjusting the current curve to a fourth-order polynomial and the power curve was adjusted according to an exponential curve, and also in this same curve, an extrapolation was made. When

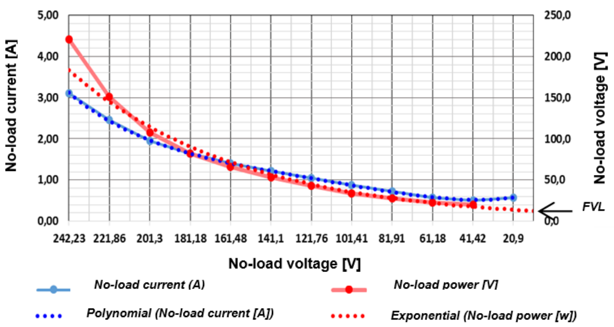

Fig. 12 Graph of current and power against voltage for separation of electromagnetic and mechanical losses in the induction motor.

extrapolate the curve it is possible to find the power with voltage equal to zero, therefore, there are no electrical losses but mechanical losses, which are friction and ventilation. These are indicated in the graph by FVL (Frictional and ventilation losses), and this case, the value was 12 Watts.

Since in the rated no-load voltage condition the losses have been determined, the no-load power Joule can be obtained. For this purpose the value of the motor resistances between phases, connected in delta, was measured, obtaining the values:

$$R_{AB\ (measured)} = 9.48\ \Omega$$
$$R_{BC\ (measured)} = 9.41\ \Omega$$
$$R_{CA\ (measured)} = 9.38\ \Omega$$

For the delta connected motor the resistance values for each resistance branch per phase is calculated by Eq. (1):

$$\boldsymbol{r_1} = \frac{3}{2}\boldsymbol{R}_{(\boldsymbol{measured})} \qquad (1)$$

Where:

$\boldsymbol{r_1}$: resistance per motor phase;

$\boldsymbol{R}$ *(measured)* → resistance measured between two phases.

Applying the equation, the real values are obtained for each of the motor phases, namely:

$$\boldsymbol{r_1} = 14.30\Omega;\ \boldsymbol{r_2} = 14.22\Omega \text{ e } \boldsymbol{r_3} = 14.01\Omega$$

And the average to be used in the calculations will be:

$$\boldsymbol{R_{med}} = \frac{\mathbf{14.30+14.22+14.01}}{\mathbf{3}} \Rightarrow \boldsymbol{R_{med}} = \mathbf{14.18}\,\Omega$$

The joule loss in the stator is calculated, in the empty condition, by:

$$P_{Jo} = 3 * 14.18 * \left(\frac{2{,}41}{\sqrt{3}}\right)^2 \Rightarrow \boldsymbol{P_{Jo} = 82\ W}$$

Finally, the engine iron losses are calculated, as follows:

$$\boldsymbol{P_{iron} = 149 - 82 - 12 \Rightarrow P_{iron} = 55W}$$

3.3 Locked Rotor Test

Total Joule copper losses can be obtained from the locked rotor test. To obtain the saturation effect, a rotor-locked voltage of approximately half of the nominal motor voltage was applied for a short time, as shown in Table 2. Note that the mean values are calculated by the relay.

3.4 Analysis of No-Load and Locked Rotor Tests

With the data obtained in the no-load test, the parameters of the motor magnetizing branch can be obtained. Test values with a locked rotor can be obtained motor dispersion parameters.

In this article, the interest is to analyze engine behavior in terms of energy efficiency. Check operational aspects against the operation in an electrical system with unbalanced voltages. Thus the values of previously performed tests will be used for the analysis of engine performance. For an analysis of the engine behavior under load, two further tests of the engine operating under load were performed.

3.5 Tests Carried Out Under Load Engine

To demonstrate the functional conditions of the

Table 2 Locked rotor assay data.

Unsaturated values							
Current (A)				**Voltage (V)**			
I_A	**I_B**	**I_C**	**I_M**	**V_{AB}**	**V_{BC}**	**V_{CA}**	**V_M**
2.7	2.9	2.8	2.8	58.1	59.3	59.0	58.8
Active power [W]			210	**Power factor**			0.74
Saturated values							
5.3	5.4	5.4	5.40	112.1	112.3	113.2	112.5
Active power [W]			772	**Power factor**			0.77

SEL-849 relay, the motor rated load test was performed considering two situations: initially monitoring the load at rated current and in another condition considering the rated speed. The data obtained from the trials were entered in Table 3.

To calculate the voltage unbalance, IEEE recommendations were adopted, which is expressed by Eq. (2).

$$unbalance\% = \frac{3(V_{máx} - V_{min})}{V_{AB} + V_{BC} + V_{CA}} . 100 \qquad (2)$$

It should be noted by analyzing Table III that under the condition that the current was monitored, it reached the nominal value well before the rotation, which was 1704 RPM. But when the nominal rotation was monitored, the current was above the nominal value.

It should be emphasized that from an operational point of view the electrical engineer is faced with an ambiguous decision: choose operating point by current or rotation?

It should be added that if the choice is by the current the efficiency will be better from the point of view of energy efficiency. If the choice is for rotation the motor should operate with a torque on the nominal axis and requiring nominal power, but with greater losses.

It is known that motors should be specified according to their thermal limit, which is a consequence of the engine operating cycle, so for a better decision one should consider using thermal limit analyzes during the engine operating cycle.

Table 3 Engine load test data.

Test data with rated current							
Voltage (V)			Current (A)			W	RPM
V_{AB}	V_{BC}	V_{CA}	I_A	I_B	I_C	P	n
219.3	221.9	220.3	2.8	2.8	2.8	672	1704
$V_{L(medium)}$		220.5	I_{LM}		2.8	*	*
Fd%		1.2%	*	*	*	*	*
Test data with nominal speed							
V_{AB}	V_{BC}	V_{CA}	I_A	I_B	I_C	P	n
219.9	221.8	220.6	3.0	3.1	3.1	798	1680
$V_{L(medium)}$		220.8	I_{LM}		3.1	*	*
Fd%		0.88	*	*	*	*	*

Consideration should also be given to the effects of voltage unbalances on losses and power on the motor shaft, according to studies published in Ref. [5].

Finally, it should be noted that the service life of motors is a direct function of heating. And to solidify this statement one cannot forget the rule established by Montsinger obtained in his research and published in Ref. [6].

3.6 Thermal Test of the Engine Under Load

The SEL-849 relay also has an interface with analog inputs that can be used to monitor motor conditions. Important variable in the analysis of electric motors is their temperature rise. This directly influences the useful life of electric machines, as, according to studies carried out, the elevation of the temperature above the maximum limit of the motor insulation system can cause the insulation between the coils to dry out, thus compromising the motor operation. It should be added that the calculation of the temperature rise allows the sizing of the motors considering their operational cycle. This subject will be the subject of future work.

The temperature values were acquired using type J thermocouples, which are temperature sensors widely used in the industrial environment. The temperature values selected by the thermocouples were sent to the program that monitors these values at the pre-defined times.

In the programming of the relay, the thermal class of the machine was defined and if the values monitored by the sensor exceeded the maximum temperature, the relay would act signalling and sending a trip signal to turn off the motor. The values of the motor thermal test consisted of raising the temperature curve against time, as shown in the motor thermal curve (Fig. 13).

The motor used on the bench is of insulation class F, which supports the value of 155°C at the hottest point of the motor. From the test, it is observed that the curve has a faster growth at the beginning, but later the curve tends to stabilize at a certain value. In this case, the motor has its temperature stabilized close to 105°C,

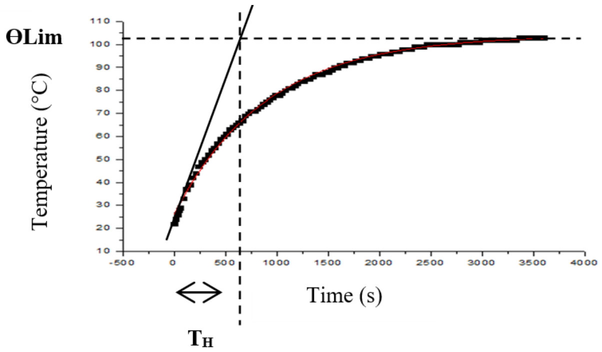

Fig. 13 Thermal curve of the 0.75 Hp three-phase induction motor with rated load and voltage.

proving that the motor works within a safe range, ensuring that at its hottest point it is close to 155°C. The thermal constant of the motor is also obtained from the curve; in this case, the TH value obtained was approximately 650 seconds or 10.83 minutes.

4. Conclusion

Tests using the SEL-849 relay provided significant information to draw the following conclusions:

1) Digital relays due to mass memory and processability allow them to be used not only for monitoring and protection of electrical systems but also for the use of these functions for other purposes as shown in this article for relay SEL-849.

2) When motors are affected by power quality phenomena such as voltage unbalances, ambiguities may occur to define the motor operating point.

3) The energy dissipated in the motor stator in the presence of unbalances is unevenly distributed between the windings of each phase and may form the so-called hot spots.

4) It is noted that given the ambiguities in the choice of motors, it is recommended that an analysis of the thermal behavior during the operating cycle is performed.

Acknowledgment

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References

[1] Switchgear Committee of the IEEE Power Engineering Society, “IEEE Standard Definitions for Power Switchgear”, Revision C37.100-1981, EUA, March 1992.

[2] Current Differential and Overcurrent Relay, Pullman, Washington USA, 2000-2012 by Schweitzer Engineering Laboratories, Inc.

[3] IEEE Std 112™-2004, “IEEE Standard Test Procedure for Polyphase Induction Motors and Generators”, 3 Park Avenue, New York, NY 10016-5997, USA.

[4] Chuck Yung and Travis Griffith, Core Loss Testing: a good procedure gone astray, *IEEE Industry Applications Magazine* (Jan./Feb. 2011) 57-64.

[5] B. N. Gafford, W. C. Duesterhoeft and Jr. e C. C. Mosher, Heating of induction motors on unbalanced voltages, *artigo apresentado no AIEE Winter General Meeting*, Feb. 1st, 1959, pp. 289-286.

[6] L. F. Blume, A. Boyajian, G. Camili, T. C. Lennox, S. Minneci and V. M. Montsinger, *Transformer Engineering: A Treatise on the Theory, Operation, and Application of Transformers* (2nd ed.).