A Digital Motor Protection Relay for HT Motors

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Abstract— Medium voltage 3-phase motors are very reliable and robust, but as modern designs operate much closer to their thermal limits and to give adequate protection, intelligent and advanced protection relays are required. In addition, increased industrial use of power electronics leads to corruption of power systems and unless specific equipment is installed to eliminate the corruption it can cause considerable rotor overheating. Motor protection relays are capable of monitoring and diagnosing long-term failure, based on the information collected and processed by powerful data acquisition systems. This paper presents a Digital Motor Protection Relay to protect High Tension motors, an IED using state-of-the-art technology, which monitors various quantities at power system level and provides all the basic protection functions, including the thermal overload protection, which is specially designed for motors.

Keywords— *motors; failure; power systems; protective relays; monitoring; thermal overload*

I. INTRODUCTION

Modern power systems require high degree of reliability. A system during its operation may develop some trouble or may produce some abnormal condition of operation, which may cause damage to the equipment. Some of the situations are unavoidable and beyond human control. Therefore, a real-time algorithm is required to detect such fault conditions and react quickly in order to minimize adverse impact[1]. This monitoring function is efficiently managed by a intelligent electronic device, known as the protection relay, which continuously monitors the grid parameters (such as voltages & currents) and switches the appropriate devices in faulty conditions. Most of the data processing happens in the digital domain. So, these devices are called as Digital or Numerical Protection Relays.

Electric motors are workhorses of any industrial plant, and often run critical processes. The motors rated below 3.3kV are called as Low Tension (LT) Motors and those ranging from 3.3kV to 11kV are High Tension (HT) Motors. Electricity consumption by motors in manufacturing sector like oil, gas and mining industries is around 90%. Thus, motors are a significant investment. But statistics reveal that despite of their reliability of operation and simplicity of construction, annual motor failure rate is around 3-5% per year. Downtime in a factory can be expensive and, can also exceed the cost of motor replacement. Hence, a proper machine protection is required to minimize the motor failure rate, prevent damage to equipment associated and to ensure production targets along with personnel safety [2].

This paper discusses the development of a digital protection relay for 3-phase High Tension motors which protects the windings in the stator from damages due to various electrical faults like over current, earth fault, over voltage, under voltage and thermal overloads. The proposal is to fully design the protection device by using digital / numerical technology, i.e. all the processing phases like signal filtering, protection and control functions will be implemented through digital processing. The technique used here is fundamentally based on Fast Fourier Transformation (FFT), which requires a 32 bit Digital Signal Controller. The relay will sound an alarm and activate the trip circuit in case of the fault according to the preset threshold of the parameter in order to minimize the damage to the motor. LEDs will indicate the faults and a graphical display shall display various measured parameters and phasor diagrams. Also, a fault disturbance record will be maintained, which can be helpful for further fault analysis.

II. LITERATURE REVIEW

Protective relaying in industrial and utility power systems has tremendously evolved since the beginning of system protection over a hundred years ago. Electromechanical relays were the defacto protection devices when no microcontrollers were available. These were ideally suitable for simple protective functions of individual loads, but not preferable for complex system[3][4]. In the 1970s, solid-state static relays replaced the EM relays with a slight change in protection scheme. The design consisted of analog circuits for detection of current/voltage value, instead of coils and magnets. After the detection of input signal, a comparator circuit determined the overload condition. But, various design problems occurred during designing of static relay[3][4]. The first generation microprocessor based numerical relays then brought innovations in developing new algorithms and the beginning of combining several protection functions in one multifunction relay package. Major difference in analog circuits here was the use of analog to digital converter[3][4].

The Digital Motor Protection Relay is equipped with a powerful digital signal processor, more reliable surface-mount construction, improved algorithms and protection elements. These developments have provided relay protection engineers with new protection schemes and advanced the quest for more reliable, more secure, and more dependable operation. These relays have built-in test routines, a “watchdog”, that signals an alarm output, & the operators know when the relay fails.

A report on “Large Motor Reliability Survey of Industrial and Commercial Installations”, published by the IEEE Motor Reliability Working Group gives results of IEEE surveys on motor reliability and major causes of motor failure[5]. A summary of these results is shown in Table.

TABLE I. SUMMARY OF IEEE MOTOR RELIABILITY SURVEY

Failure Contributor	Percentage
Overload	30%
Insulation damage	20%
Phase failure	14%
Bearing damage	13%
Ageing	10%
Rotor damage	5%
Others	8%

The various limitations found in presently available relays are[6]:

- Phase angle error while detection.
- Limitation of analog input range
- Noise and malfunctioning problems on field.
- Less communication capabilities.
- Low precision in calculation of analog inputs.
- Slow response time in decision making.
- Non volatile data storage.
- Less facility of disturbance record.

III. DESIGN METHODOLOGY

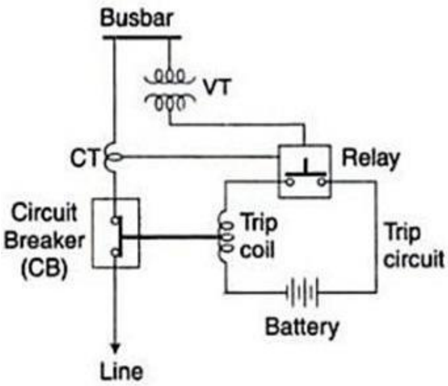

Fig. 1. Simplified Diagram of Relay Operation

Figure shows the basic operation and location of relay. CB isolates the faulty part of power system in case of abnormal or fault conditions. A protective relay detects abnormal conditions and sends a tripping signal to CB. When fault occurs in the line the relay connected to CT & VT detects the fault, actuates and closes its contacts to complete the trip circuit. Current flows from battery into the trip circuit. As the trip coil of CB is energized, the CB opens to disconnect the faulty element[3].

A. Hardware Designing

The complete system is divided into three steps: Signal conditioning & analog to digital conversion, performing FFT on all the signals, and using the output of FFT for various protection algorithms.

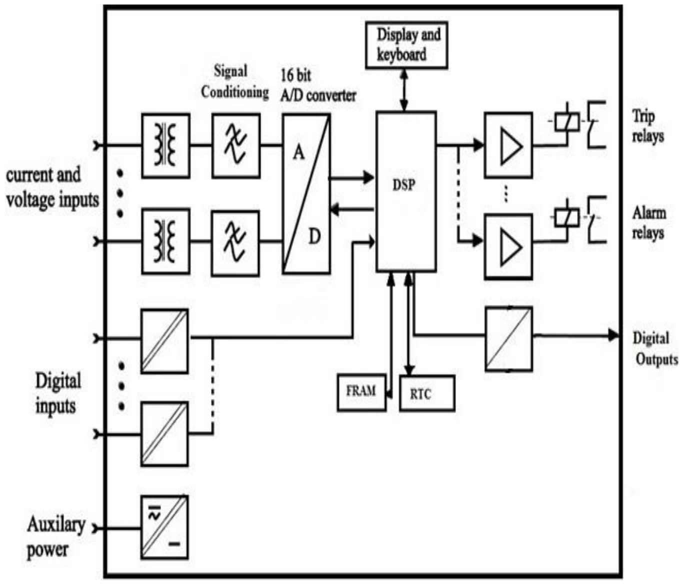

Fig. 2. Architecture of Digital Motor Protection Relay

The relay samples 3-phase quantities at power system level. Current and Voltage Transformers are used in electrical power system to step down the system current and voltage to a safe value for further processing. Transformers provide electric & static isolation between analog input variables and internal electronic circuits. Here, we have provide common terminals for two configurations of CT, a 1A/2mA and 5A/10mA CT. The range of input current for desired protection range is 5% to 4000% of the rated value, which is 50mA to 200A. Similarly, for a 63.5V/591mV VT, the range is 5% to 200% of the rated value, i.e 3V to 127V. This output is applied to Signal Conditioner or analog input subsystem.

Signal Conditioning brings real world signals into the digitizer. This block includes a high precision instrumentation amplifier used to condition small signals in the presence of large common-mode voltages and DC potentials, and a non inverting amplifier to enhance adjustable increase the gain. Table shows the measured voltages for both sections at different test points, assuming injected current as 5A, and injected voltage as 63.5V for R, Y and B phase.

TABLE II. CT & VT SECTION

Parameter	TP 1 Instrumentation Amplifier	TP 2 Non-inverting Amplifier
CT Section	91.382 mV	182.705 mV
VT Section	2.28 V	4.56 V

Also the signal conditioning circuit takes the responsibility of reducing the noise and other interferences which can distort the incoming signal. The outputs of Signal Conditioner containing the phase information are applied to the analog to digital converter.

A high speed, low power, 8-channel, 16-bit, simultaneous sampling, SAR ADC is used with true bipolar pre selectable input range of ± 10V. It samples at throughput rates up to 200 kSPS for all channels. Start of conversion (SOC) signal frequency of 1600 Hz (32 samples/cycle) is used for simultaneous sampling of all channels. The end of conversion (EOC) signal issued by ADC indicates that the conversion over and the data is ready to read. The time taken by the ADC to convert all eight channels is about 2 µs. The digitized output of the ADC over its entire operating range is tested and tabulated as below.

TABLE III. DIGITIZED OUTPUT OF ADC

Input voltage (V)	Hex output code
10V	7FFFH
5V	3FFFH
0V	0000H
-5V	C000H
-10V	8000H

After sampling and quantization by ADC, analog electrical signals are represented by discrete values of samples taken at specified instants of time. On calculating full scale range for ADC by considering 5% to 4000% of the rated value, the ADC range that we require is 0.135mV to 9V. So we can select analog input range as ± 5V, by configuring the RANGE pin of ADC to low. Also, the status of Circuit Breaker is fed to the ADC via digital input subsystem. Digital Inputs allows the DSC to detect logic states. The output from ADC is fed to the Digital Signal Controller.

The TMS320x Series Delfino generation processor by Texas Instruments, is a highly integrated, high-performance solution for demanding control applications. It is a 32-bit CPU with single precision Floating Point Unit (FPU), and enhanced control peripherals. It has ability to operate at upto 150 MHz The Digital Signal Controller processes the signals in form of discrete numbers by a incorporating a relaying algorithm using numerical methods. A relaying algorithm which processes the acquired information is a part of the software. The algorithm uses Fast Fourier Transform (FFT) technique to estimate the real and imaginary components of fundamental voltage and frequency phasors. This is the fastest method by which we can carry out DFT[7].

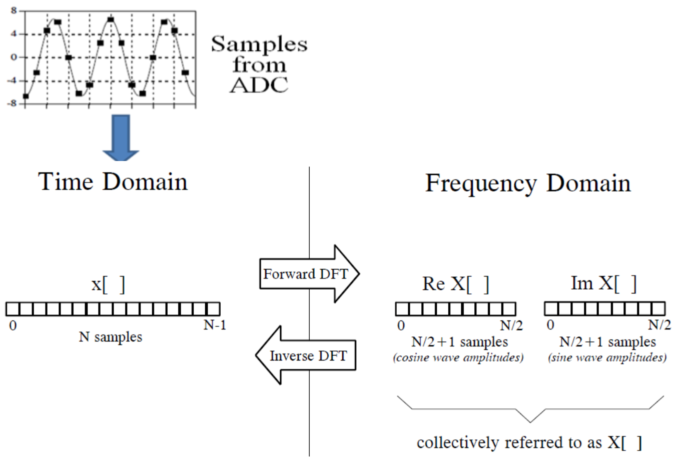

Fig. 3. DFT Terminology

In the time domain, *x*[ ] consists of *N* points running from 0 to *N*-1. In the frequency domain, the DFT produces two signals, the real part, *ReX*[ ], and the imaginary part, *Im X*[ ]. Each of these frequency domain signals are *N*/2 + 1 points long, and run from 0 to *N*/2. The Forward DFT transforms from the time domain to the frequency domain, while the Inverse DFT transforms from the frequency domain to the time domain[7].

The FFT takes the sampled signal in time domain as input. This time domain signal is the sine wave obtained from power signal also containing superimposed harmonics. Since we are not aware of the actual frequency of the signal, we sample according to 50 Hz signal at a sampling rate of 1600 Hz. So, 32 samples are to be taken for each cycle. Fig. 5 shows the FFT output, which are real and imaginary terms.

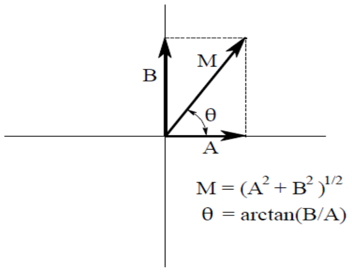

Fig. 4. FFT output in polar notation.

FFT states that, for an n-sample input, we obtain N/2 real and imaginary terms. So, for 32 samples/cycle, we will get 16 real and 16 imaginary terms, 0-15. The 0th real and imaginary term gives us the DC value of the signal, this can be discarded. The 1st real and imaginary term gives the fundamental component in rectangular notation.

The computed quantities are compared with predefined thresholds to decide whether the system is experiencing a fault or not. If there is a fault, the relay sounds an alarm or sends a trip command to the circuit breakers to isolate the faulty zone of power system. The trip output is transmitted to the power system through digital output subsystem. Digital Outputs allow a DSC to output the logic states.

It is important to know the occurrence of an event, fault, and its type, and the time at which it occurs. This is done by Real Time Clock by giving time stamps at regular intervals. Ferro-electric random access memory (FRAM) is used to store the fault records and relay settings which determine functioning of the device. A graphical display is provided to view the relay features, system voltages, current phase angle values and various settings. Keypad is used to configure the relay input parameters.

B. Software Designing

The software for the motor protection relay is developed in embedded C language using Code Composer Studio, (CCSv5.4)®. is used as a development tool. CCS by Texas Instruments is a Eclipse-based integrated development environment (IDE) for developing routines on a wide variety of their DSPs. In CCS, the editing, code generation, and debugging tools are integrated into one unified environment[11].

The various protection functions and necessary settings for the digital motor protection relay have been developed in the software. Following subsections give a brief idea about the same.

1) Over Current Protection: Over current is a situation where a current of high magnitude, than intended, exists through a conductor, which may lead to damage to the equipment. Over current protection is used against the heavy over loads and short circuit faults [1][3][8]. This protection function measures the fundamental frequency components of the phase currents. The protection is sensitive for the highest value of the3-phase currents. Whenever this value exceeds the user set value, that stage picks up and an Alarm signal is generated. If the fault persists to occur for longer time than the estimated trip time configured in the relay, a Trip signal is issued. There are two adjustable over current stages: definite time (DT), known as Instantaneous or High Set Phase Fault Over Current Protection, or inverse time operation characteristic (IDMT), known as Time Delayed Over Current Protection. Fig. 5 shows functional block diagram for over current protection function.

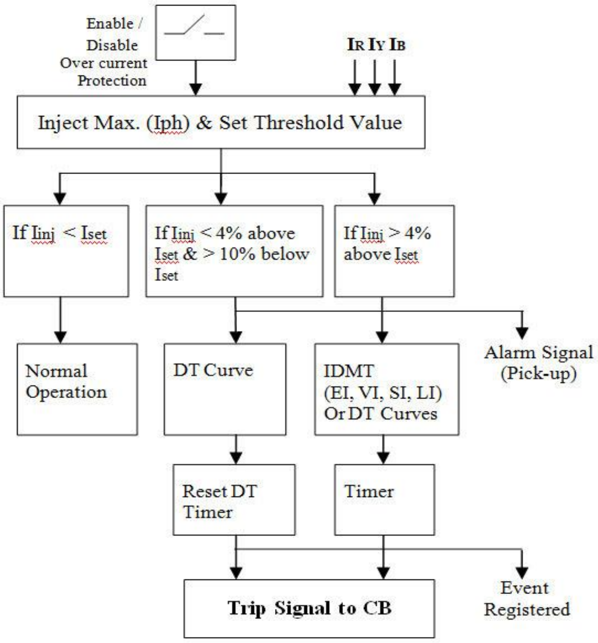

Fig. 5. FBD for Over Current Protection

This function can be activated by changing the function setting to ENABLE. A threshold is defined ranging from 5% to 4000% of rated current, in steps of 1%. The highest of the three phase currents is sensed and compared with the threshold value by the comparator. There are three possible conditions in this case:

a) If injected current is less than set current: No alarming or tripping occurs, & normal operation continues.

b) If injected current is 4% above the set current: The relay starts picking up. This current is known as pickup current, and an alarm signal is generated. Further, according to the type of time - current characteristics chosen in curve setting (IDMT or DT), the timer calculates the delay. If IDMT curves are selected, which includes SI1, SI3, EI, VI, LTI curves as defined by IEC Standards, the operation time depends on magnitude of the current. Operation time decreases as current increases. If DT curve is chosen, relay operates after predetermined time when current exceeds its pickup value. Here, the operational time is constant, & irrespective of the magnitude of the current. A trip signal is issued to the breaker at the end of this delay.

c) Hysteresis: When comparing an injected value against pickup value, some amount of hysteresis is needed to avoid oscillations/ fluctuations near equilibrium condition, i.e if the injected current is fluctuating near the set threshold, it may lead to ambiguous situation. To perform accurate decision making in this case, a pick up current and a dropout current is defined above and below the set threshold, where pickup current is 4% above the threshold value & drop out current is 10% below the threshold value. In case of DT operation, as soon as the alarm signal is issued, an added feature of RST DT is included. This is a Reset DT Timer, & its value corresponds to the minimum time during which the current value needs to be lower than 90% of the phase threshold before the corresponding phase time delay is reset.

At the every instant at which the trip signal is issued, an event is also time stamped, and saved in the fault record, wherein the timings & causes of the fault and tripping can be found out. The following equation gives the time delay in over current protection of various IDMT curves can be referred for calculation of delay.

$$t = \frac{K}{[I/Is]^{\alpha} - 1} \times Tm, \text{ where} \quad (1)$$

I = injected current

Is = set current

Tm = Time Multiplier Setting

K and α are constants, and their values differ for different curves as shown in the Table.

TABLE IV. VALUES FOR CONSTANTS

Curve	K	α
SI-3	0.14	0.02
SI-1	0.061	0.02
VI	13.5	1.0
EI	80.0	2.0
LTI	120.0	1.0

2) Derived Earth Fault Protection: A fault which involves ground is an earth fault, and it occurs due to failure in motor winding or supply cable insulation between one or more conductors & ground. The earth fault protection function is sensitive to the fundamental frequency component of the 3Io, which is the sum of all the phase currents, IR, IY & IB, known as residual current. Under normal conditions, residual current is zero.[1][4][10] When an earth fault occurs, the residual current is non-zero. Whenever this value exceeds the set value by the user, that stage picks up and Alarm signal is generated. If the fault situation persists to occur for longer time than the estimated trip time configured in the relay, a Trip signal is issued. The operating principle & functional block diagram for earth fault is similar to that for over current protection function as seen in Fig. 5.

3) Thermal Overload Protection: This a condition where the temperature rise of the stator or rotor exceeds the design criteria, typically caused by a failure to start, excessive loading or failure of the motor cooling system (high ambient temperature and blocked ventilation). The purpose of thermal overload protection is to protect the motor insulation from excessive thermal stresses. It ensures that the thermal withstand of the machine is not exceeded, at the same time allowing full use of the motors thermal capability[2][3][8]. The relay performs thermal imaging of the motor from the line current and the negative component of the current consumed by the motor, by considering the thermal effects created in the stator and rotor. The harmonic current components contribute to the motor's heating. Thermal overload protection detects short- and long-term overloads under varying load conditions. The heating up of the motor follows an exponential curve, equivalent value is determined by the squared value of the load current. The full load current of the motor determines the thermal trip level of thermal element.

IV. TESTING

The digital motor protection relay hardware was evaluated for all types of fault. Real time test signals were generated by DOBLE F6150 power system simulator, which is a highly configurable test equipment[12]. The simulator uses state-of-the-art signal processors and power amplifiers to deliver a high power, lightweight simulator for all protection testing applications. It allows dynamic state testing and transient simulation testing using 12 independently controlled sources in a single instrument. The F6 Control Panel is a virtual front panel which provides "point-and-click" control of all sources, inputs, outputs and timers. It can perform operating time tests for up to eight separate events. The above mentioned faults and their trip times were calculated theoretically, and later compared with the results obtained by F6150 Simulator.

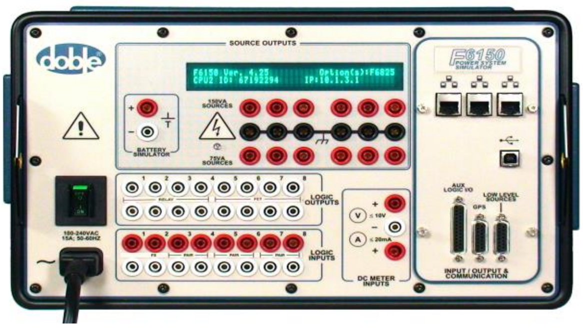

Fig. 6. F6150 Power System Simulator

V. CONCLUSION

Digital Protection Relays are critical elements in any power distribution subsystem. In order to avoid catastrophic failures, these relays should employ high-speed and high-accuracy electronics. Applications like motor protection require different techniques and input/output capabilities. Depending on this application we have undergone systematic study for designing such type of electronics protection system. This embedded system should be capable of applying advanced logic. It should be capable of analyzing whether the relay is to trip or restrain from tripping depending on current or voltage values, or any other parameters set by the user, binary inputs, and in some functions, the timing and order of event sequences. Thus, the logic designed is user reconfigurable at a level well beyond simply changing the front panel switches. Thus, adequate motor protection not only prevents damage to the motor, but also ensures optimal process efficiency and minimal interruption. The cost recovery for protection is thus achieved by extending the life of the motor, preventing motor rewinds and reducing process downtimes.

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