Improving Operation and Maintenance of Substation Equipment Using Operational Data From Protective Relays

Mohamed Nabil Ali
Schweitzer Engineering Laboratories, Inc.

Presented at the
GCC Power 2019 Conference & Exhibition
Muscat, Oman
October 27–29, 2019

IMPROVING OPERATION AND MAINTENANCE OF SUBSTATION EQUIPMENT USING OPERATIONAL DATA FROM PROTECTIVE RELAYS

Mohamed Nabil Ali*
Schweitzer Engineering Laboratories, Inc.

USA

***Summary*—Most modern digital protective relays can easily monitor power system equipment and provide detailed data concerning their performance and condition. These data can be used to develop a maintenance program that ensures equipment is serviced as required and that preventive actions are taken to avoid any possible failure.**

Protective relays provide extensive information that can be retrieved and linked with operational and maintenance topologies, either manually or automatically.

This paper details the data that can be retrieved from modern digital protective relays only and how these data can be used to develop an equipment maintenance program that saves time and money. The targeted audience for this paper is electrical power engineers, power system engineers, control engineers, automation engineers, electrical maintenance engineers, and electrical power utility owners.

***Keywords*—Digital protective relay monitoring features–Automatic retrieval of operating data stored in digital protective relays–Electrical equipment maintenance enhancements.**

I. Introduction

Today, protective relays can be used for several applications outside of their original functions to protect electrical networks. Control and automation are now combined in most protective relays, and the relays can provide data from substations, analyze events, and even prevent failures in electrical devices.

Because protective relays protect electrical systems against all types of electrical faults, a very detailed and well-defined interface usually exists between the relays and the protected equipment so that the relays perform their functions accurately based on the statuses of power system equipment. This equipment includes but is not limited to circuit breakers, transformers, and motors. Through monitoring of operation data archived in protective relays, operation and maintenance engineers can retrieve useful information that reflects the accurate status of the equipment. Efficiency improvements could include "reading key equipment data from the relay and displaying or generating work instructions; reducing unscheduled downtime from equipment failures; and improving maintenance effectiveness by working on equipment based on condition instead of on a time basis [1]."

Operation and maintenance teams can retrieve and analyze a significant amount of information to enhance system efficiency, including circuit breaker coil monitoring and contact wear data, motor starting statistics, and transformer through-fault current monitoring. Documenting the appropriate information in work instructions can increase the life cycle of the electrical equipment and decrease workload by accurately scheduling a maintenance program for the equipment when really needed. This has the benefit of focusing maintenance teams' efforts and time on tasks that provide the highest return [1].

Protective relays provide detailed information about operating characteristics, the status of vital equipment, and maintenance indicators. Through organizing the monitoring features of protective relays (along with their data logs) and establishing communications channels between operation and maintenance systems, little or even no-cost information can be easily retrieved from the relays to help operators and maintenance engineers evaluate the efficiency of electrical equipment and the maintenance program needs. Accordingly, these operators and engineers can make an informed decision and schedule maintenance whenever it is required.

* Schweitzer Engineering Laboratories, Inc., 2350 NE Hopkins Court, Pullman, WA 99163 USA • papers@selinc.com

TABLE I
PERIODIC MAINTENANCE SCHEDULE FOR POWER TRANSFORMER

No.	Items to Be Inspected	Periodic Inspection Schedule				
		Every Month	Every 3 Months	Every 6 Months	Every Year	Every 5 Years
1	Ambient, oil, and winding temperature	X				
2	Ventilation for indoor transformer	X				
3	Bushing		X			
4	Relay alarms	X				
5	Oil leakage			X		
6	Earth resistance check			X		
7	Oil filtration				X	
8	Overall inspection					X

This paper details the information that can be extracted from digital relays and how the information can be used to create a robust maintenance program.

II. MAINTENANCE DEFINITIONS

There are many definitions used to specify the meaning of maintenance and its types, models, and procedures. Put simply, maintenance can be defined as the required process need executed within a specific time frame to ensure efficiency and high performance over the life cycle of equipment. Several actions can be taken based on that process, such as repairing or replacing defective or unhealthy components or devices, to guarantee overall system efficiency.

III. MAINTENANCE TYPES

In electrical power systems, maintenance is essential to ensure the healthy operation of all equipment in the network—from generation plants to the transmission network, substations, and distribution network—so power reaches consumers safely, continuously, and efficiently.

Several types of maintenance have been defined, and these types are differentiated by the time of execution, periods, process, action required, and action taken per the tasks that they include.

A. Periodic Maintenance

Periodic maintenance is the basic maintenance of equipment performed by equipment users. It is also defined as time-based maintenance.

It includes a series of basic tasks (e.g., data collection, cleaning, visual inspection, and so on). An example of this model of maintenance is shown in Table I.

B. Preventive Maintenance

Preventive maintenance is the best type because it guarantees the high performance of equipment by providing a maintenance program exactly when it is needed (i.e., when the equipment is likely to fail but before it actually fails). Hence, it maintains the highest reliability of the equipment and eliminates unplanned system shutdown, ensuring the maintenance program is efficient without commitments with a fixed time frame.

C. Corrective Maintenance

Corrective maintenance is the worst type because it includes tasks targeted to correct equipment failures that require sudden and unplanned interruption of service to consumers.

IV. MAINTENANCE PROGRAM

It is always best to switch from unnecessary periodic maintenance to preventive maintenance because it rapidly reduces the outage of live circuits. In addition, maintenance is performed only when it is needed, saving time and money.

Without a proper maintenance schedule that aligns with manufacturer recommendations for each piece of equipment, electrical equipment can misoperate or fail to perform their main function, which will result in performing corrective maintenance. This is the least desirable maintenance because it takes the system out of service suddenly and without warning, and it is very costly to return it back to service within a short period of time. Power system operators try to avoid this type of maintenance at all costs.

There are many reasons that power system operators should invest in maintenance programs, including the following:

- Reduce corrective maintenance
- Reduce overtime wasted with low productivity
- Improve customer service
- Migrate from scheduled maintenance to preventive maintenance

Having an efficient maintenance program requires accurate monitoring of all power system equipment to determine whether or not equipment needs maintenance. Today, digital protective relays can easily provide this accurate information through their built-in monitoring features.

V. Power System Structure

Power system networks consist of various types of equipment with different levels of power and functions. They contain generation, transmission, and distribution devices, as shown in Fig. 1.

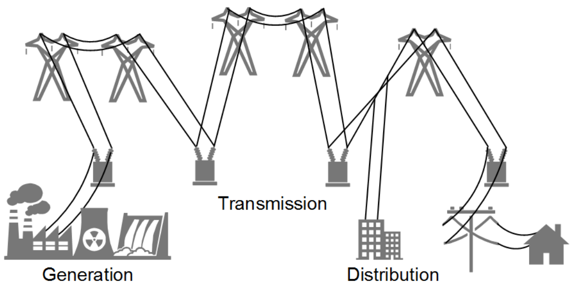


Fig. 1. Power System Diagram

A digital relay, a type of intelligent electronic device (IED), is a computer-based system with software-based protection algorithms that detect electrical faults. It is a smart device that receives inputs, such as analog values (current, voltage, resistance, and so on) or digital values (e.g., binary digits) and compares them to set threshold values. It then provides outputs (virtual or physical) accordingly.

Fig. 2 is a simplified depiction of how the protective relay interfaces with the power system.

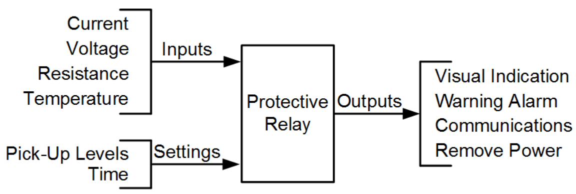


Fig. 2. Protective Relay Overview

A protection system is a combination of the following devices, which together provide a comprehensive solution for monitoring and protecting electric power systems (see Fig. 3).

- Protective relay
- Circuit breakers
- Current transformer
- Voltage transformer
- Communications channels
- Power supply system (ac, dc)
- Control cables

More details on the types of protective relays and their functions can found in [2].

Today, a protective relay combines multiple functions. It has a processor that can be used to perform several processes at the same time, and it communicates with local and remote devices installed over the power network. However, it is most often used to protect a specific and unique application in the power system.

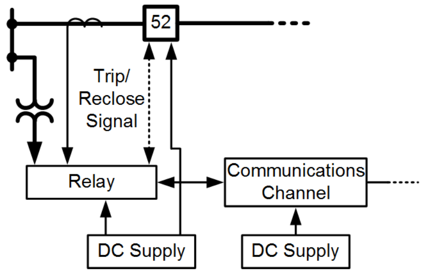


Fig. 3. Protection System Structure

Generators, transmission feeders, transformers, bus bars, capacitors, reactors, and motors require standalone relays with multiple protection functions to protect against any faults that may affect their performance.

Because a protective relay already interfaces with the protected equipment, it can also be readily used to monitor the health of the equipment it protects. Protective relays store this information in nonvolatile memory in various report formats, which can be retrieved at any time to monitor the protected device.

Reference [3] provides further details on the highly reliable and trustworthy information provided by digital relays.

VI. Circuit Breaker Monitoring Feature

A circuit breaker is an electrical switch that operates automatically based on instructions from protective relays to interrupt current flow during a fault condition.

Because of the circuit breaker's importance in the power system, the circuit breaker manufacturer must specify its characteristics in terms of the maximum current that can flow in the breaker's poles, the number of operations (close or open), and even the time delay between each operation and the following one.

A protective relay controls the circuit breaker operation and can issue a trip command to open the circuit breaker during fault events. Further, it can be used to close the circuit breakers once the fault is isolated.

A protective relay interfaces with a circuit breaker through its auxiliary contacts (52a indicates the circuit breaker is in close status and 52b indicates it is in the open status).

As shown in Fig. 4, through current transformer (CT) inputs, relays can also measure the current passing through the circuit breaker poles in all conditions, including switching, running, and even in fault mode. With this information, protective relays can monitor the number of operations and the current values for each operation, which can be used to generate detailed reports. These reports can be used to schedule a preventive maintenance program aligned with the circuit breaker data and the breaker manufacturer recommendations.

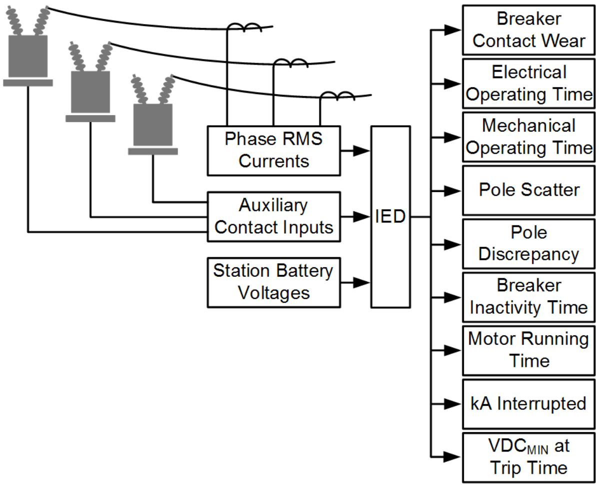


Fig. 4. Circuit Breaker Interface With Relays and Relay Monitoring Reports

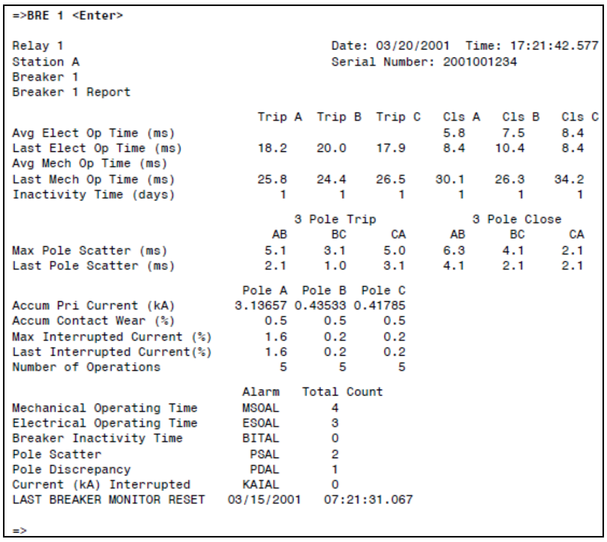
The circuit breaker monitoring features in protective relays can provide the following data (also shown in Fig. 5), which can be used to measure the circuit breaker performance and determine if it needs maintenance:

- Circuit breaker wear
- Electrical and mechanical operating time
- Circuit breaker inactivity time
- Interrupted current
- Pole discrepancy
- Motor runtime

Using the circuit breaker wear monitoring feature provides a clear view of the number of close or open operations and the accumulated interrupted current flow in the circuit breaker pole during breaker open operations. The relay can be programmed to trigger an alarm when the actual wear curve (see Fig. 6) intersects the circuit breaker manufacturer curve.

The actual measured circuit breaker operating time should match the circuit breaker nameplate information provided by the manufacturer. If it does not, the circuit breaker should be repaired.

Interrupted current should also be within the maximum withstand value specified by the manufacturer. If the current exceeds this value, immediate maintenance should be performed to ensure the breaker is still functioning properly.


```
=>BRE 1 <Enter>

Relay 1                                   Date: 03/20/2001   Time: 17:21:42.577
Station A                                 Serial Number: 2001001234
Breaker 1
Breaker 1 Report

                                Trip A   Trip B   Trip C    Cls A    Cls B    Cls C
Avg Elect Op Time (ms)                                       5.8      7.5      8.4
Last Elect Op Time (ms)          18.2     20.0     17.9      8.4     10.4      8.4
Avg Mech Op Time (ms)
Last Mech Op Time (ms)           25.8     24.4     26.5     30.1     26.3     34.2
Inactivity Time (days)              1        1        1        1        1        1

                                     3 Pole Trip               3 Pole Close
                                   AB       BC       CA       AB       BC       CA
Max Pole Scatter (ms)             5.1      3.1      5.0      6.3      4.1      2.1
Last Pole Scatter (ms)            2.1      1.0      3.1      4.1      2.1      2.1

                                Pole A   Pole B   Pole C
Accum Pri Current (kA)         3.13657  0.43533  0.41785
Accum Contact Wear (%)            0.5      0.5      0.5
Max Interrupted Current (%)       1.6      0.2      0.2
Last Interrupted Current(%)       1.6      0.2      0.2
Number of Operations                5        5        5

                                Alarm   Total Count
Mechanical Operating Time       MSOAL       4
Electrical Operating Time       ESOAL       3
Breaker Inactivity Time         BITAL       0
Pole Scatter                     PSAL       2
Pole Discrepancy                 PDAL       1
Current (kA) Interrupted        KAIAL       0
LAST BREAKER MONITOR RESET   03/15/2001   07:21:31.067

=>
```

Fig. 5. Protective Relay Circuit Breaker Monitoring Reports

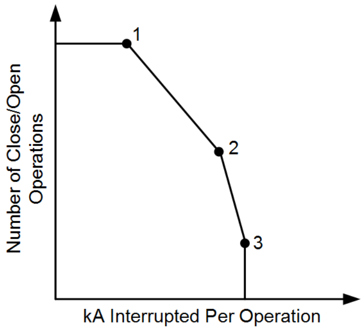


Fig. 6. Circuit Breaker Wear Contact Curve

VII. Motor Monitoring Feature

Electrical motors play a very important role in the power system. They deliver the required energy to the mechanical loads to start movement and produce the output.

Several parameters defined by the motor manufacturer can be used to monitor motors, such as the maximum starting current, starting time, time between start, maximum start per hour, maximum overload withstand value, and so on. All of this information can easily be retrieved from a protective relay, which is used to protect the motor and monitor motor operations and data.

Using a protective relay to collect motor data—operation counters, starting and running time, thermal capacity, motor winding temperature, and so on (see Fig. 7)—is the easiest and fastest way to schedule a maintenance program based on the actual status of the motors.

```
Operating History (elapsed time in ddd:hh:mm)
Last Reset Date      12/23/2011
Last Reset Time        14:06:26
Running Time         >  0:01:24
Stopped Time            0:00:48
Time Running (%)           63.4
Total MWhr (MWhr)           1.9
Number of Starts              2
Emergency Starts              0

Avg/Peak Data
                  AVERAGE     PEAK
Start Time (s)        0.3      0.3
Max Start I (A)     200.5    201.0
Min Start V (V)    4165.0   4165.0
Start %TCU            4.9      9.8
Running %TCU         31.9     44.5
RTD %TCU              0.0      0.0
Running Cur (A)     197.8    198.9
Running kW         1345.7   1434.0
Running kVARin      472.2    751.3
Running kVARout       0.1    252.4
Running kVA        1427.7   1436.5
Max WDG RTD (C)   Fail     Fail
Max BRG RTD (C)   Fail     Fail
Ambient RTD (C)   Fail     Fail
Max OTH RTD (C)   Fail     Fail

Learn Parameters
Start TC (%)  Insufficient Data
```

Fig. 7. Motor Statistics

With each start attempt, a motor protection relay can trigger a starting report that includes all starting details, including the starting current, starting time, and thermal capacity during startup (see Fig. 8). It can also include electrical parameter information, such as the voltage drop during starting and the motor speed and slip.

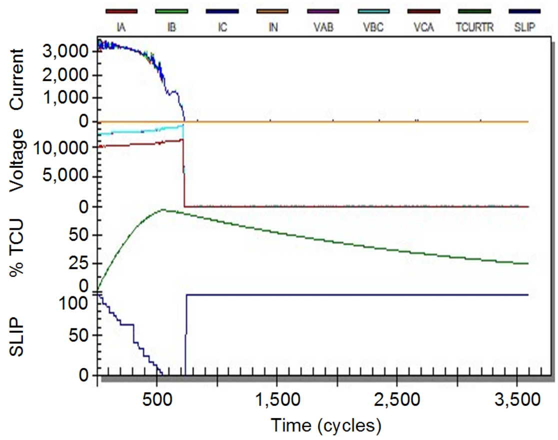


Fig. 8. Motor Start Report

Analyzing these data can determine if the motor is running as per manufacturer recommendations or if it needs maintenance to rectify any issue.

VIII. Transformer Monitoring Feature

A power transformer is the muscles of a power system network and the heart of any grid or utility network. A transformer converts the voltage levels between two, three, or even four different values, so it always requires a high level of attention from the protection functions.

The transformer consists of iron-magnetizing coils, electrical windings, insulations, and bushings. These electrical and mechanical protection elements enable each transformer to cover any fault in the mechanical parts and/or the electrical circuits of the transformer.

Transformer protection relays protect against any electrical fault and interface with the built-in mechanical protection systems associated with transformers to facilitate the integration of mechanical alarms or trips through remote monitoring and control systems such as a supervisory control and data acquisition (SCADA) system.

Transformer protection relays can monitor in-zone and out-of-zone faults. They can also monitor any thermal stress on the transformer windings that results from heavy fault currents for both internal and external faults and provide a detailed report containing current values, winding temperatures, and thermal stress whenever needed.

Thermal modeling, mechanical alarm and trip levels, and the through-fault current profile can be retrieved from the relay and used to analyze the state of the transformer.

During through faults, heavy fault current flows through the transformer windings and CTs located on each side of the windings to the fault location. To avoid an undesired operation during an external fault, the protective relay should be set so that the fault is cleared if the downstream protection system does not respond to isolate it. This will protect the transformer and its auxiliary equipment (such as both windings and CTs) from any thermal damage or mechanical stress (see Fig. 9).

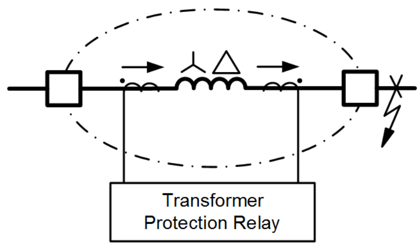


Fig. 9. Transformer Protection Relay Connection During External Fault

Each transformer has a thermal and mechanical damage curve (see Fig. 10), which can be used as a reference for setting protection functions to avoid transformer damage [4].

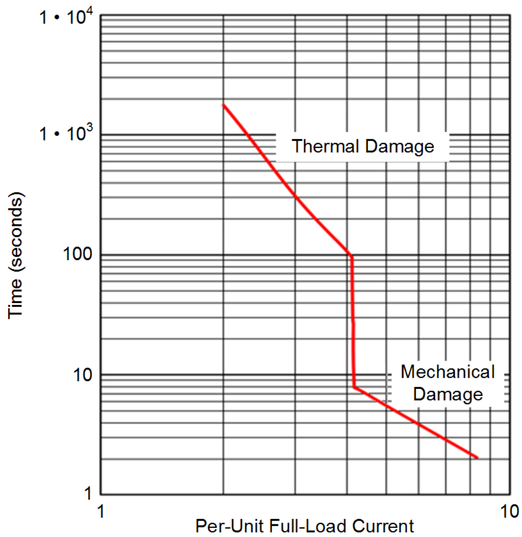


Fig. 10. Transformer Damage Curve [5]

In addition to electrical wiring, protective relays can treat all mechanical alarms through hardwire signals from the mechanical relays associated with the transformer tanks and send them to remote monitoring and control systems to report the status of the transformer and provide detailed information. An example of this information is the through-fault report in Fig. 11. This information can be used by operators and maintenance engineering teams to determine if preventive maintenance is required.

```
Winding 1
Total Number of Transformer Through Faults: 4
Total Number of A Phase Through Faults:     2
Total Number of B Phase Through Faults:     1
Total Number of C Phase Through Faults:     1

Total Accumulated Percentage of Through Fault Capability:
                    A-Phase     B-Phase     C-Phase
                    95.97       60.00       60.00
Through Fault Alarm: 0          0           0

Last Reset: 04/03/2014 15:16:27

#   DATE       TIME         Duration   IA    IB     IC    A      B     C    Alarm
                            (seconds)  (max primary kA)    (Increment %)
1   04/03/2014 15:23:37.102 19.983    1.99   0.00   0.00 35.97  0.00  0.00
2   04/03/2014 15:20:23.256  1.663    0.00   0.00   3.28  0.00  0.00 50.94 ABC
3   04/03/2014 15:20:19.918  1.675    0.00   6.37   0.00  0.00 99.99  0.00 AB
4   04/03/2014 15:20:16.596  1.650    1.99   0.00   0.00  2.97  0.00  0.00 A
```

Fig. 11. Transformer Through-Fault Report

IX. DC Battery Monitoring Feature

Another useful feature that protective relays provide is the dc battery system monitoring feature. The dc battery system is one of the most important systems in a substation. It is responsible for delivering all control and protection dc supply to secondary systems in the substation.

Protective relays can monitor dc battery systems and provide the following information:

- Voltage level changes
- Earth leakage
- AC ripple on the rectifier

The relays can automatically monitor the health of the station battery system by measuring these values between each battery terminal and ground, and the results can guide the user to understand how much the station dc battery voltage dips when a tripping or closing command is issued.

The battery monitor feature allows the user to force the relay to assert an alarm if the monitored quantities are outside of values specified by the manufacturer.

X. Load Profile Feature

Load profile is another general monitoring feature available in protective relays.

The load profile includes a variety of monitoring features that can be used to track analog quantities, such as current, voltage, power, frequency, power factor, and harmonics, within a specific period to analyze the change in load conditions.

This feature is very useful for power system planning engineers who decide whether it is necessary to expand the network capacity by adding more generation, transformers, feeders, and so on, or shed unnecessary loads. They can easily do this based on data provided by the load profile feature in the protective relay (see Fig. 12).

There is flexibility in setting the interval method and its period for each analog quantity. Some relays have a very high memory capacity that can accommodate many years of load profile registers (sometimes as much as 20 years).

#	DATE	TIME	IAW1_MAG	IAW1_ANG	IBW1_MAG	IBW1_ANG	ICW1_MAG	ICW1_ANG
23	2014/01/14	16:16:40.992	0.099	0.000	0.225	-52.125	0.344	-108.435
22	2014/01/14	16:21:40.270	124.580	0.000	124.853	-119.627	123.668	120.426
21	2014/01/14	16:26:40.157	124.346	0.000	124.902	-119.358	123.626	120.711
20	2014/01/14	16:31:40.019	124.309	0.000	124.886	-119.598	123.973	120.577
19	2014/01/14	16:36:40.024	124.293	0.000	124.836	-119.361	123.403	120.631
18	2014/01/14	16:41:40.056	124.559	0.000	124.813	-119.709	123.970	120.493
17	2014/01/14	16:46:40.275	124.249	0.000	124.774	-119.646	123.907	120.574
16	2014/01/14	16:51:40.333	124.589	0.000	124.671	-119.569	123.603	120.483
15	2014/01/14	16:56:40.908	0.088	0.000	0.188	45.000	0.395	-26.565
14	2014/01/15	17:01:40.934	124.293	0.000	124.842	-119.504	123.485	120.619
13	2014/01/15	17:06:40.972	124.490	0.000	124.758	-119.463	123.546	120.518
12	2014/01/15	17:11:40.038	124.341	0.000	124.741	-119.297	123.424	120.779
11	2014/01/16	17:16:40.045	124.320	0.000	125.130	-119.517	123.630	120.623
10	2014/01/16	17:21:40.295	124.476	0.000	124.687	-119.537	123.518	120.455
9	2014/01/16	17:26:40.070	124.284	0.000	124.874	-119.413	123.649	120.818
8	2014/01/16	17:31:40.168	0.129	0.000	0.182	106.928	0.210	49.399
7	2014/01/17	17:36:40.215	124.313	0.000	125.154	-119.530	123.752	120.662
6	2014/01/17	17:41:40.803	124.383	0.000	124.992	-119.613	123.796	120.550
5	2014/01/17	17:46:40.282	124.446	0.000	124.799	-119.464	123.600	120.444
4	2014/01/17	17:51:40.077	124.432	0.000	124.710	-119.774	123.728	120.379
3	2014/01/17	17:56:40.114	124.288	0.000	125.274	-119.590	123.905	120.605
2	2014/01/17	18:01:41.047	124.392	0.000	124.730	-119.483	123.404	120.576
1	2014/01/17	18:06:41.020	0.210	0.000	0.099	-8.130	0.182	-57.529

Fig. 12. Load Profile Report

XI. Automatic Retrieval of Electrical Equipment Data Logs From Digital Protective Relays

Fast and secure organized data reporting is essential for ensuring an accurate and timely maintenance decision to guarantee maximum reliability of substation equipment.

All data archived in digital protective relays can be retrieved through two methods: manual polling or automatic retrieval.

The first option is to access all data and reports manually by establishing a communications link to the relays and manually selecting the required data or reports. However, it may take considerable amount of time and requires periodic checks for any new stored events and/or reports in the protective relays. Conventionally, the system operators collect the required data periodically or each time an event occurs in the system by sending personnel to the substation and manually collecting the required data or reports from the relays. The collected data is then sent to the operators. Many maintenance engineers use this method.

Because of remote locations and/or bad weather, this important information may not be available to operations and maintenance staff in a timely manner, which leads to delays in corrective actions and a negative impact on electrical system performance.

The second option is to automatically retrieve the digital relay data logs, which is possible because of innovative technology in the substation automation sector. Ethernet-based communications allows the exchange of information between digital protective relays and control centers instantly with high-accuracy time stamps through fast and secure communications protocols.

Real-time data can be automatically retrieved from digital protective relays through a communications link with SCADA systems, and the reports and data logs can be displayed through the SCADA human-machine interface (HMI) graphically or in text format.

Integration of IEDs with a centralized SCADA system allows many maintenance tasks to be automated, limiting the occurrences of human error due to manual operation.

Today, most of the electrical power network is monitored and controlled from a centralized control center connected to all substations in the network, which facilitates remote access to all substation devices to gather the required information whenever it is needed.

Substation automation and control systems (such as the one shown in Fig. 13) consist of different layers, starting with protective relays and other IEDs that provide most of the system information that the operator needs to monitor in the control center. This layer is followed by automation and communications layers, which contain Ethernet switches, computers, gateways, firewalls, and so on. The highest layer consists of the operational database, along with software installed in the control center used to visualize all retrieved information from IEDs.

Through this system implementation, unique benefits can be obtained, which include but are not limited to the following:

- Remote monitoring and control of all substation equipment.
- Remote access to IEDs.
- Ability to create a database that contains all system logs.
- Historical alarms and events.
- Ability to alarm the operator of any issue in the system under control.
- Full protection against unauthorized access to the system.

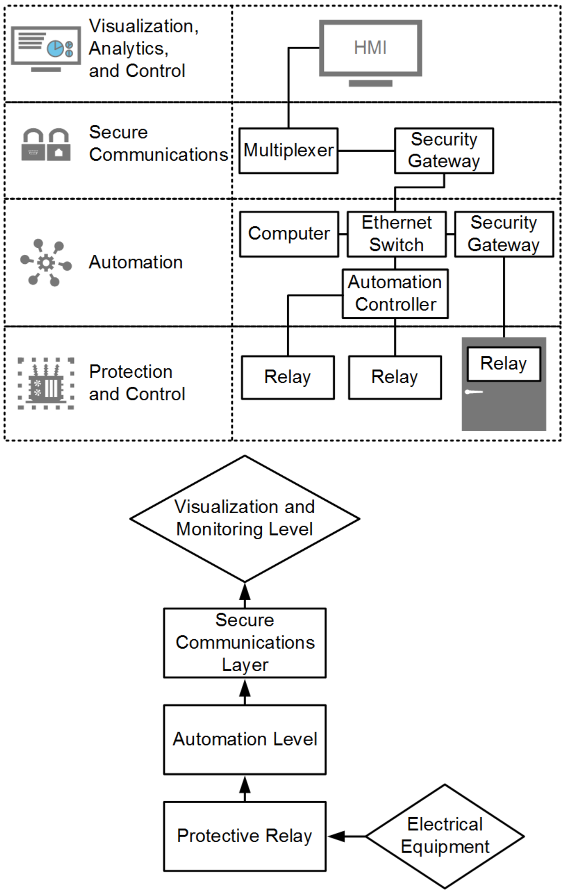


Fig. 13. Substation Automation and Control System

XII. Scheduling a Maintenance Program Based On Data Logs In Digital Protective Relays

Various quantities can be tracked by digital relays, and those can be used as an indicator of the protected equipment status.

The monitoring feature in relays provides the ability to obtain protected equipment operating data in report format. Alternatively, the data can be integrated with the SCADA system through binary signals asserted by the relay based on setting threshold levels defined by the user.

Upon retrieval of this data from digital protective relays, a simple comparison can be done to determine whether or not the current values match or are within the acceptable limits defined by the equipment manufacturer.

This comparison content is different based on the nature of the application; however, a common format must be used to ensure all essential and important parameters are addressed properly. An example of this comparison model for a motor maintenance application is shown in Table II.

Table II
Motor Maintenance Application Comparison Model

Electrical Parameters	**Values Based On Motor Data sheet**	**Actual Values From Motor Protective Relay**	**Remarks**
Starting current	6 • FLA	5.3 • FLA	Within limits (pass); no action required
Starting time	6 seconds	6.9 seconds (per motor start report)	Out of limits fail); action required
Full-load amperes (FLAs)	350 A	400 A (per load profile)	Out of limits (fail); action required

XIII. Conclusion

Protective relays provide valuable data that can be used to ensure equipment receives maintenance only when it is really needed. Information recorded and stored within IEDs can further provide situational awareness of the overall electric network. Since protective relays are already an essential part of the system, the data they provide is almost free. Knowing and understanding data features in protective relays is essential for realizing significant savings in time, cost, and production loss.

Relay monitoring data can automatically be retrieved from substations to the control center through substation monitoring and control systems, making the development of a robust maintenance program even easier.

Gathering archived operational data from relays and comparing those with the data sheets and specifications of each piece of equipment is an effective way to schedule a maintenance program to prevent unexpected failures in the electrical power system.

XIV. References

[1] M. Zeller, "Convert Operational Data Into Maintenance Savings," proceedings of the IEEE Rural Electric Power Conference, Fort Worth, TX, May 2014.

[2] H. J. Altuve Ferrer and E. O. Schweitzer, III (eds.), *Modern Solutions for Protection, Control, and Monitoring of Electric Power Systems*, Schweitzer Engineering Laboratories, Inc., Pullman, WA, 2010.

[3] R. D. Kirby and R. A. Schwartz, "Microprocessor-Based Protective Relays Deliver More Information and Superior Reliability With Lower Maintenance Costs," proceedings of the 42nd Annual Industrial & Commercial Power Systems Technical Conference, April 2006.

[4] R. Moxley and A. Guzmán, "Transformer Maintenance Interval Management," proceedings of the TechAdvantage Conference and Expo, San Diego, CA, February 2005.

[5] IEEE C57.109, IEEE Guide for Liquid-Immersed Transformers Through-Fault-Current Duration, 1993.

XV. Biography

Mohamed Nabil Ali received his B.S. degree in electrical power and machines engineering from the Faculty of Engineering at Helwan University in Egypt in 2007. He has almost 12 years of experience in power system protection, including work in protection design and the testing and commissioning of high-voltage (HV) and extra-high-voltage (EHV) substations. In 2007, he joined Electric Power System Engineering Company (EPS) as an electrical power design engineer in control and protection. He later joined ALFANAR, where he worked as a lead testing and commissioning engineer for the protection and control system in HV and EHV systems for almost 5 years. In 2013, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as a senior protection application engineer and is a SEL University certified instructor.

20190524 • TP6922-01