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Development of Protective Relaying Equipment in Substations

RANRAN LIN
Department of Electrical and Communications Engineering
Helsinki University of Technology
P.O.Box 3000, FIN-02015, HUT
FINLAND

Abstract: - This paper mainly discusses the development of protective relaying equipment in substations. As electronics and computer technologies progress, more original electromechanical relays (EMRs) in substations are being replaced by advanced semiconductor-based relays, say, solid-state relays (SSRs), and some microprocessor-based automatic protective relaying equipment, so that there is a remarkable increase in the degree of substation automation than before. In addition, to deal with the increasingly complex grid, programmable logic controllers (PLCs) are widely used as a type of protective relaying equipment in the substation automation due to their high flexibility and reliability.

Key-Words: - protective relaying equipment, SCADA, EMR, SSR, microprocessor-based relay, PLC

1 Introduction

In the power system, substations play an important role in determining the stability of the grid and they should execute right action as soon as possible to keep the whole grid run normally even if some faults happen.

In the past, substations are usually controlled by the operators, while today it is not enough to deal with such complex functions just by the operators. Also, substations should be always properly monitored and controlled to take necessary precautions accurately and timely. Owing to the development of automation technology, that more automatic equipment is used in substations brings about substation automation.

Nowadays the substation automation usually includes a supervisory control and data acquisition (SCADA) system, which enables a cost-effective remote control system that is capable of monitoring real time operating conditions and controlling the performance of substations. SCADA system can provide both real time status information and historical information about the equipment in substations. The basic SCADA system consists of three components: remote terminal units (RTUs), a master station with host computers, and communication infrastructure. The functions of SCADA system, in general, include data acquisition, data processing, status estimation, statistical analysis and failure warning so on.

Fig. 1 shows the basic structure of SCADA system. In Fig. 1, the master station located in a control center is responsible for controlling all the substations within its range. The function of controlling each substation is performed by the RTUs in the substations. At first, the RTUs send real time data to the master station via a high-speed communication channel, and then the master station, after receiving and analyzing the data, may give commands to the RTUs to determine what action should be performed in case of faults, for example, open a circuit breaker (CB). Next, the RTUs give signals to the relays or programmable logic controllers (PLCs), and then the relays or PLCs can do associated action on the CBs and switches when receiving the signals. In practice, the relays and PLCs belong to significant protective relaying equipment that directly carries out the control over the CBs and switches.

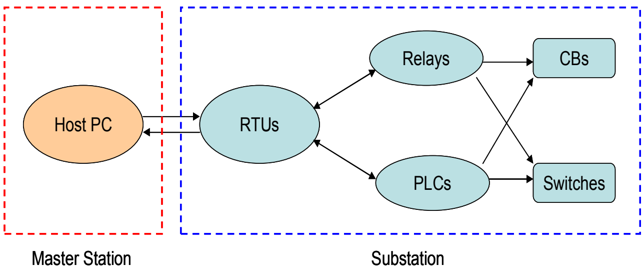

Fig. 1. The basic structure of SCADA system and the relation among RTUs, relays and PLCs.

2 Relays

In the substation automation, relays are a type of automatic equipment which can send warning signals to the operators or can trip CBs to isolate a faulty part from the grid when some faults happen, so that the grid may not be affected seriously and can still run as before.

Many facts show that as the grid becomes increasingly complex, the possibility of faults in the grid will rise greatly. Usually two common phenomena occur during the operation of the power system. One is overloading, which results in a current exceeding the rated value, and the other is short circuit, under which case the value of a current may be many times larger than its normal value. These phenomena can cause serious problems in the grid because of the large current, which may have severe damage to both the faulty part and a healthy part of the grid, even lead to the loss of synchronism and hence the collapse of the whole grid.

In the modern substation automation, protective relaying aims at detecting and isolating the faulty part as quickly and as selectively as possible by relays. A well-designed protective relaying system should fulfill the following requirements:

- Reliability, meaning that the protection is capable of detecting all types of faults;
- Selectivity, expressing that the protection can only isolate the faulty part from the grid;
- Quickness, meaning executing associated action rapidly;
- Sensitivity, indicating that within its effective range, the relay should have some margin in the sensitivity.

Normally, CBs and switches, which are applied to switching the power transmitted along the transmission lines on and off, are directly controlled by relays. At present, there are three main types of relays used in the substation automation, namely, electromechanical relays, solid-state relays, and microprocessor-based relays.

In spite of their complex structure, the working principle of the relays is simple. In brief, a relay includes an input circuit and an output circuit, as well as a driving circuit that forms the coupling between the input and output circuits. Signals coming from transducers are sent to the input circuit, then the driving circuit responds to the inputs, and finally with the effect of the driving circuit the outputs will be produced in the output circuit. Usually the output circuit of the relay is connected with CBs to produce contact closed signals used to trip the CBs or warning signals to the alarm panel.

2.1 Electromechanical Relays

Electromechanical relays (EMRs) are the first generation of relays used in the power system and have been used for many decades. Fig. 2 demonstrates the basic connections of a traditional EMR, which was given by A.R. van C. Warrington in [2]. The EMR is used to control the trip coil of the CB which controls the transmission lines. When the current flowing along the transmission lines is larger than the rated value, the current flowing in the current transformer (CT) will be larger as well. In a similar way, the higher the phase voltage is, the larger the current in the potential transformer (PT) is. Then the larger current either from the CT or from the PT flows along the coils in the relay and produces strong electromagnetic force which makes the relay contact S closed. After that, the high L/R ratio of the trip coil of the CB delays the build-up of the current so that the CB is tripped before the current reaches its steady value. And then, its auxiliary switch K opens the highly inductive trip coil circuit and the EMR can reset when de-energized by opening the CB [2].

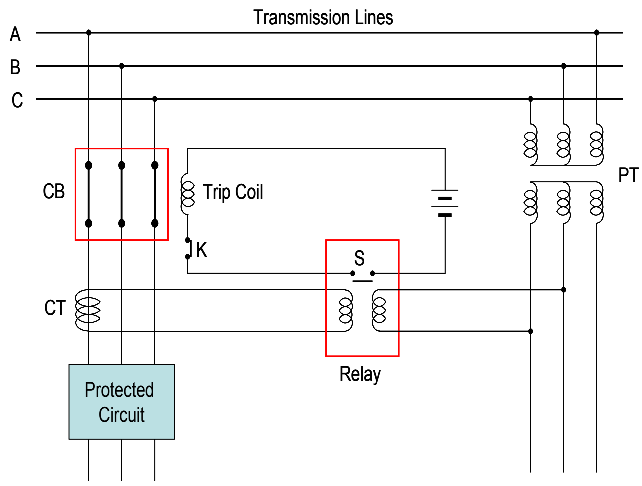

Fig. 2. The basic connections of a traditional electromechanical relay.

EMRs are extremely useful because it can be implemented that using small a current or voltage controls a large current or voltage for the purpose of safety. The relay coil producing the electromagnetic force only consumes a fraction of power, while the contact closed or opened by that electromagnetic force is able to conduct a large amount of power to the load. In effect, EMRs work as a binary amplifier with two states, on and off.

In addition, inside the relay, there is not any mechanical contact between the input circuit and output circuit, which means that the input part and output part are electrically insulated from each other.

2.2 Solid-State Relays

Although EMRs realize electrical insulation to some extent, under some special circumstances, such as extra high voltage (EHV), the electrical insulation will

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not be effective any more. Thus, solid-state relays (SSRs) appeared. An SSR is a control relay with absolute electrical insulation between the input part and output part. Its coupling part is achieved mainly by means of the light, instead of the electromagnetic field in traditional EMRs. Semiconductor components, such as light emitting diodes (LEDs) and transistors, are used to implement the coupling, so SSRs belong to semiconductor-based relays. They are quite ideal for applications with many contact closures since they offer a greatly extended life, in comparison with EMRs.

SSRs work similarly to EMRs, as shown in Fig. 3, since both of them use an input circuit and a separate driving circuit for switching the power. When the voltage is applied to the input of the SSR, the relay switch is energized by LED. Then, the light from LED is beamed into the light sensitive semiconductor, which, in the case of zero voltage crossover control relays, conditions the driving circuit to turn on the output of the SSR at the next zero voltage crossover.

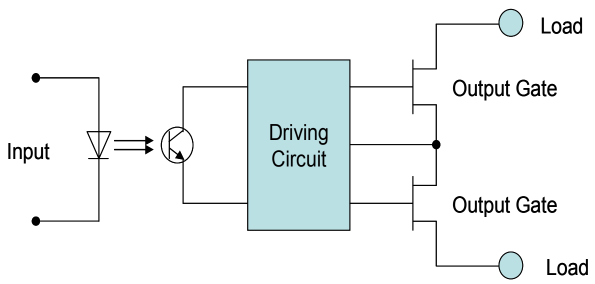

Fig. 3. The basic structure of an SSR.

In the case of non-zero voltage crossover relays, the output of the SSR is turned on at the precise voltage occurring at the time. Removal of the input power disables the driving circuit and the SSR is turned off when the load current passes through the zero point of its cycle.

By comparison with EMRs, SSRs have the following main features:

- Anti-shock and anti-vibration;
- A long life;
- Absolute electrical insulation;
- Switching without causing arc;
- Zero voltage switching;
- Short response time;
- Good compatibility with transistor-transistor logic (TTL), diode-transistor logic (DTL) and high-threshold logic (HTL).

2.3 Microprocessor-Based Relays

Owing to the complex functions of substations, single-function relays, for example, SSRs, cannot meet the needs for the modern substation automation. As microprocessor technology tends to be more mature, in the 1960’s a microprocessor-based relay was brought about. The microprocessor-based relay has a trend that it is taking the place of traditional relays due to its powerful functions and enough convenience.

It is well known that traditional protective relaying schemes have typically been made up of discrete components such as overcurrent relays, distance relays, timing relays and so forth. All the relays must be wired together to form a complete and functional scheme, which means costing too much time and money during the process of design, development and installation.

Microprocessor-based relays, however, provide many advantages over the schemes using discrete components. The overall scheme takes up less panel space, easier design and wiring. Furthermore, the number of components as well as the installation testing and maintenance testing is also greatly reduced. Microprocessor-based relays offer many advanced features and functions in addition to their basic protection functions, for instance, fault locating, event reporting and analog quantity metering.

Therein, the fault locating function has become a standard feature in nearly all the microprocessor-based relays. This function may greatly improve the working efficiency and may also be used to evaluate the faulty area in the transmission lines in terms of the real time values of fault current and impedance.

Next, the event recording function provides data about internal relay element operation and the real time waveforms of current and voltage. The event data obtained by this function is of importance in evaluating the performance of the relays and the whole system.

At last, microprocessor-based relays can take the place of some transducers and can provide analog quantity metering along the transmission lines, which can be directly sent to RTUs, such as current, voltage, active power and reactive power.

3 Programmable Logic Controllers

It is undoubted that microprocessor-based relays have improved the stability of the grid greatly. However, another problem is coming. The structure of the grid sometimes needs to be changed. Thus, all the relays have to be configured again because the structure and functions of the equipment are fixed. Hence, the protective relaying equipment with quite flexible structure is in great demand for substations.

The appearance of programmable logic controllers (PLCs) makes this problem easily solved. A PLC is a user friendly, microprocessor specialized computer that can handle Boolean operations to carry out the control functions of many types and levels of complexity. The PLC produces an on or off voltage output and can actuate such equipment as CBs and switches, so it is a good substitute for relays in the substation automation due to its excellent flexibility.

The basic operation of PLCs corresponds to a microprocessor-based equivalent of a relay panel. Nonetheless, PLCs can also execute other operation that traditional relays cannot realize easily, such as counters and delays. In addition, PLCs are much more flexible than any type of relays, because they can implement different functions just by changing the program written in easy languages or diagrams instead of configuring the relays again. A single PLC, therefore, can replace hundreds of relays, which is quite economical and convenient especially under the conditions of the increasingly complex substation automation.

The first PLC was initially developed in 1968. Then in 1977 a microprocessor-based PLC was introduced in the US and it was based on Intel 8080 microprocessor with circuitry to deal with Boolean logic instructions at a high speed [3]. Several decades later, today different categories of PLCs, which depend on their input/output (I/O) capacity, memory capacity and other parameters, and they can meet all the needs in the modern substation automation.

Despite of the size, function and I/O capacity, the basic structure of the PLC is almost the same. O. Gustaf, et al., demonstrated the basic structure of a PLC in [3], as shown in Fig. 4.

In Fig. 4, there are three main parts in the PLC: an input part, an output part and a control part consisting of a central processing unit (CPU), an accumulator and a memory [3]. When the power of the PLC is turned on, the PLC initially does a quick sanity check to ensure that all the hardware is working properly. In case there is a problem, the PLC will halt and will give an indication. Finishing the sanity check, the PLC will then scan all the inputs which are usually from sensors, switches or transducers, and then the inputs are read into the input register. The input register is often not only a bit but a byte, so one input instruction is capable of giving the states of eight different input ports [3]. Hence, this is Phase 1 when the PLC is running.

Next, the instructions fetch the values stored in the input register and send them to the CPU. The CPU is the core component in the PLC and it can carry out both algebraic and logical operations. According to the program written into the memory beforehand, the CPU will do associated operation in terms of the values obtained from the input register. The values, with which the CPU is working, obviously, are not current values, but stored values. The CPU can work towards a result register or an accumulator, and the result of an instruction is stored either in some intermediate registers or directly in the output register [3]. This is Phase 2 during the process of PLC's running. This phase will be done again and again until the program in the memory is executed completely.

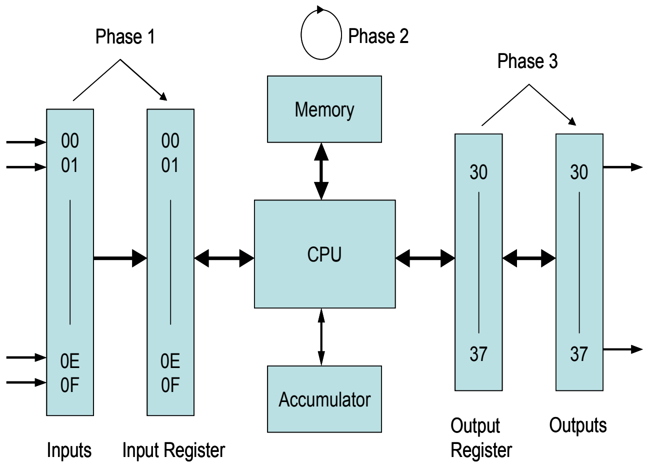

Fig. 4. The basic structure of a PLC.

After the complete execution of the program, the outputs will be scanned so that the results from the CPU can be sent to the output register, and then to the outputs. In general, the outputs are connected with relays. This is the last phase when the PLC works.

It is undoubted that the PLC, to some extent, was brought about with the evolution of the control engineering for several decades. In the past, it is factitious operation that was the main approach for controlling protective relaying equipment. More recently, electricity has been used for this kind of control. The development of microprocessor technology has brought about the most significant revolution, PLCs, a good replacement for relays.

PLCs have been gaining popularity in substations and will probably remain predominant for some time. This is related to the advantages of PLCs:

- Cost effectiveness for controlling complex systems;
- Strong flexibility, which means that a PLC can be applied to controlling systems with different structure;
- Strong computational ability for both algebraic and logical operations, indicating that it is allowed to do more sophisticated control;
- Easier troubleshooting, which can be carried out by programming;
- Reliability, meaning that components may make PLCs operated for many years without any failure.

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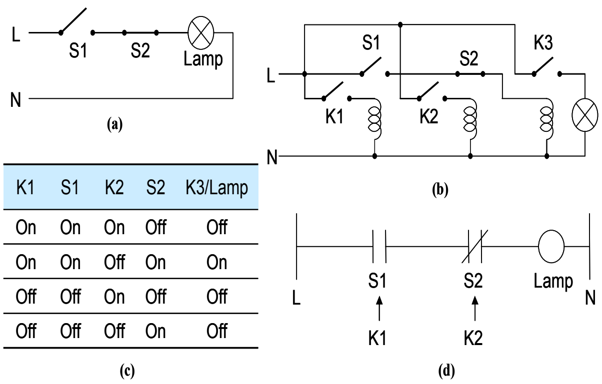

K1	S1	K2	S2	K3/Lamp
On	On	On	Off	Off
On	On	Off	On	On
Off	Off	On	Off	Off
Off	Off	Off	On	Off

Fig. 5. The implementation of the ladder logic of a PLC: (a) A switch circuit; (b) An equivalent relay circuit; (c) A truth value table; (d) An equivalent ladder diagram.

As discussed earlier, PLCs are quite flexible due to their programmable ability. As to the programming in the PLC, the most common method is using relay-type ladder diagrams instead of writing languages.

K.T. Erickson demonstrated a simple example about what the relay-type ladder diagram is and how it can be implemented in [6], as shown in Fig. 5 here. Fig. 5(a) shows a basic switch circuit for lighting, and S1 and S2 are two switches. Under the normal conditions, S1 is open while S2 is closed. Apparently, the lamp will work if S1 turns closed. The associated equivalent circuit carried out by relays is shown in Fig. 5(b). K1, K2 and K3 are the contacts of three relays. Also K1 and K2 link with S1 and S2, respectively. If K1 turns closed while K2 remains open, both S1 and S2 will be closed. Then K3 will be closed with its relay tripped by closed S1 and S2, and then the lamp will light. It is easy to see that total three relays are used in such a simple circuit [6]. Next, with the application of the PLC, the equivalent circuit will be much easier, which is expressed in Fig. 5(d). In fact, what Fig. 5(d) shows is a simple relay-type ladder diagram. The symbol of S1 is referred to as normally open contact (NOC), and that of S2 normally closed contact (NCC). Fig. 5(c) lists a truth value table. Only when K1 turns closed and K2 open, that is, both S1 and S2 are closed, does the lamp work. In practice, the ladder diagram will be scanned and executed in Phase 2 when PLC working and then the associated result will be sent to the outputs. It is intuitive that the equivalent circuit in Fig. 5(d) is quite simple in comparison with that in Fig. 5(b). Furthermore, if the switch circuit is changed, it is enough to just change the ladder diagram by programming again, and no needs to change the configuration of the relays. As a result, PLCs are a good substitute for the traditional relays.

4 Conclusions

The implementation of the substation automation is an effective approach to ensure the stability of the power system. One of the key parts in the substation automation is protective relaying equipment which directly controls CBs and switches, for example, relays and PLCs. Although the grid is becoming increasingly complex, the equipment should work with enough reliability and flexibility.

Relays are a type of significant protective equipment with a long history. From EMRs, to SSRs, then to microprocessor-based relays, they are developing towards high reliability and multi-function. However, because of many complex functions in modern substations, any type of the relays has a common defect that the functions and configuration are usually fixed so the relays have to be settled again in case there is some change in the structure of the grid. It is, apparently, a difficult and time-consuming task.

Fortunately, the appearance of PLCs solves this problem. Not only can PLCs realize the functions which relays have, but also their configuration can be changed just by writing a program again. Therefore, PLCs are quite flexible and convenient for the modern substation automation, and traditional relays are being replaced by PLCs.

Nowadays, with the application of intelligent electronic devices (IEDs), there is a trend that more IEDs will be incorporated into protective relaying equipment used in the modern substation automation. It is expectable that in the future both PLCs and microprocessor-based relays combined with IEDs will be the main protective equipment and will be widely applied to the substation automation with high reliability, flexibility and intelligence.

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