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Substation automation and control in railway networks

L. Ippolito[a], F. Murolo[b], A. Piccolo[a], D. Villacci[c]
[a]*Dipartimento di Ingegneria dell'Informazione ed Ingegneria Elettrica, Università degli Studi di Salerno, Salerno, Italy*
[b]*SEPSA - Società Concessionaria Pubblici Servizi Ferroviari e Automobilistici S.p.A, Napoli, Italy*
[c]*Dipartimento di Ingegneria Elettrica, Università degli Studi di Cassino, Cassino (FR), Italy*

Abstract

This paper introduces an approach to railway substation automation and protection. It shows, after a briefly description of the typical railway substation structures, the concept of the railway substations equipped with an innovative telecontrol and automation system. In this paper the traditional protective and operative functions, which can be automated, will be pointed out and a possible automation system will be discussed in detail. Then some considerations will be made about the potential benefits and costs associated with those automated functions.

1. Introduction

Today, many studies on automation of electrical substation are present in literature, describing the possibility to achieve such advantages as system safety or energy saving with an innovative and intelligent management of electric power plants. On the other hand, the progressive development of the control and protection systems towards distributed intelligence permits their adoption also in traditional electric power plants as traction ones.

The study of the present state reveals that many substations of the various national entity for railway transportation are equipped only with classic automation equipments:

- automatic reclosing;

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- resistive earth fault analyser;
- insulation test;
- voltage regulators.

This automation lack determines such operating difficulties as delay in supply restoring, underutilisation of power transformers and feeders, high operating costs and worse working conditions, due to the necessity to use attended substations.

In this scenario, the paper investigates on the possibility to automate the railway substation with the following aims:

- increase of continuity and quality of supply;
- increase of equipments reliability and availability;
- increase of the transportation system safety;
- reduction of the operating and maintenance costs;
- reduction of energy consumptions.

Today, the adoption of a distributed control system, traction system oriented, permits both to achieve all these advantages at very low costs and to adapt them to an existing traction power system with proper substation configurations.

2. Typical railway substation

In order to identify the functions and tests which can be automated it may be useful to describe the structure of an electrical substation used in railway systems. It is typically composed of:

- HV or MV feeder(s);
- power transformers;
- semiconductor rectifier sets;
- feeding cells;
- measuring cells;
- auxiliary services;
- feeder disconnectors and switches;
- control panels.

Moreover, in an attended substation some mimic diagrams, one for each unattended substation, are added. They permit to the substation operators to perform some elementary function such as reclosing of breakers and telemeasures from remote substations.

The analysis of substation topology reveals its structural and operational complexity, which requires the adoption of an automatic system of control and protection instead of a manual system one, in order to optimise substation performance and efficiency. This kind of rough automation does not permit the optimal exploitation of the power system with obvious repercussions on the operation quality and continuity as well as on the operating profits. A set of credible or non-credible contingencies, such the contact wires or transformers misoperation, may lead the electrical system toward severe fault conditions up

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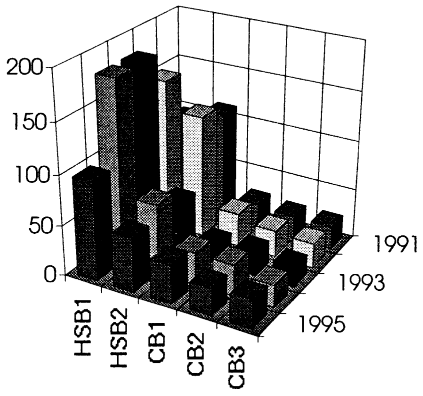
to the system outage, to which corresponds a lowering of the plant safety index.

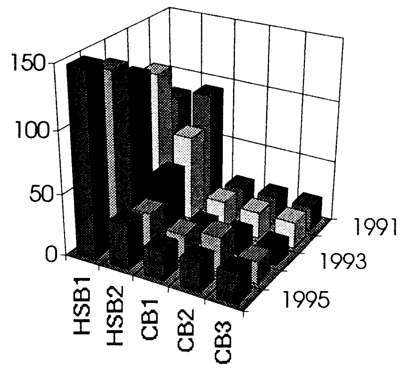
This means that the traditional control and protection systems are not able to manage such contingencies both owing to short reaction and evaluation times are required and because of these systems cannot guarantee the respect of prefixed indices of security and safety. The need to respect, according to priority, a prefixed index of security for humans (passengers and manpower) and a prefixed index of safety for plants and components precludes the chance to demand the power system restoration and reconfiguration to a human operator, giving to the automated system the task to modify the traction system operation, in presence of failure conditions, in order to guarantee the respect of the safety and security indices under the operator supervision.

Still from the point of view of an higher and higher reliability and availability of the system, it must be observed that the adoption of an automated system may represent a useful tool for a preventive maintenance, based on electric plant statistics, supporting high availability of each monitored equipment.

The needs till now exposed seem more and more clear if the substations fault statistics, showed in fig. 1, are considered.



Attended Substation



Unattended Substation

HSB1: high-speed circuit-breaker trip of line n.1
HSB2: high-speed circuit-breaker trip of line n.2
CB1: breaker trip of AC/DC converter n.1
CB2: breaker trip of AC/DC converter n.2
CB3: breaker trip of AC/DC converter n.3

Fig. 1 - Substations fault statistics.

They are relative to an urban electrified traction system, which has two electrical substations, only one is attended, equipped with traditional control systems. Data analysis shows the occurrence of about 270 faults/year for each substation, which affect the auto-reclosing high-speed circuit-breakers and the AC/DC converter breakers, particularly. It must occur to underline the

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elimination of these faults has required the manual intervention of the operator in substation, and the fault clearing time may vary from some minutes to some hours (a 7h 34min interruption has been registered), during which the operation is reduced or stopped with consequent operating loss.

Relatively to the short time interruptions (up to 2 minutes), they are not recorded and are eliminated by the auto-reclosure of the high-speed circuit-breakers, under the substation operators supervision, in order to avoid the breakers of the unattended substation are locked. In fact, if this happens it is necessary a local intervention to unlock the breakers, with an obvious increase of the fault clearing time.

The trip of the high-speed circuit-breakers, which protect the contact wires from overcurrents, is the most recurring event in the examined system because it depends both to short circuits on the wires or on-board trains and to the trains starting currents. On the other hand, if the setting of the high-speed circuit-breakers is not optimal it can cause untimely breaker trips with consequent disconnection of the contact wire, for this reason they requires periodic off-line inspection to check the relay functions in order to minimise this occurrence.

The duration and the high frequency of the aforementioned faults reveal the importance to single out the control and protection functions which are possible to automate for a better exploitation of the existing components and plants.

3 Automation function description

As aforementioned, the spreading of automation in railway substations may improve their control and maintenance and facilitate the monitoring. The first fundamental step in the design of an integrated substation control system is to make a list of functions to be automated. On this basis it is possible to consider the following functional modules which can be included in the automation system [1]:

- the control module, which performs substation switch control functions both in normal state and during restoration period;
- the monitoring module, which performs an intelligent monitoring for digital and analog parameters, giving alarm signals if one of them exceeds the normal state limitations;
- the protection module, which performs the misoperations diagnosis, using the informations coming from circuit breakers and protective relays, and the fault location function;
- the logging module, which draws up a complete and detailed report of substation plant, specifying the kind of faults, the equipments affected by faults, the fault clearing times, etc. .

All the functions, using data stored in one or more data banks, can be automated and classified in function of the performed operation as showed in tab. I.

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Table I - Functions to be automated.

Control	• remote trip, close and protection reset • automatic reclosing • service restoration
Monitoring	• circuit breaker status • trip coil monitoring • load tap changers • transformers • circuit breaker and protection alarms; • feeder loads • diagnostic (local and remote) • substation reactive power monitoring
Protection	• inverse time and instantaneous overcurrent • busbar protection • earth fault • thermal imaging • breaker failure • fault location • fault isolation
Logging	• protection, circuit breaker operating, and fault clearing times • load and fault currents

All these functions, for their complexity, diversity and interactions, require a detailed description. To the aim to obtain a suitable description of the substation automation functions, some representation methods could be adopted, among which the more efficient one appears the Petri net method [2]. It permits to represent a function as a "states machine" and to simulate all functions evolving in parallel mode, obtaining such advantages as the programming work reduction, debugging effort reduction, software documentation optimisation, etc. . In particular, this method of analysis simplify the testing stage as the Petri nets furnish an exhaustive methodology to identify the "critical stages" of each functions. Moreover, this methodology permits to convert the specifications directly into software program for PLCs, using literal languages which simplify the future software maintenance and the training of the maintenance staff.

Relatively to the architecture for this control system the choice among the possible schemes must be made on the base of operational, reliability and costs considerations. In any case it must respect such demands as modular structure and locally distributed intelligence. A possible architecture for an integrated control system is reported in fig. 2.

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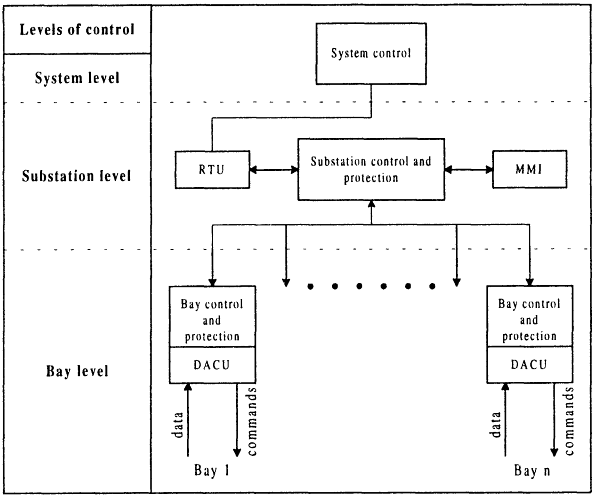

RTU: Remote Terminal Unit
MMI: Man-Machine Interface
DACU: Data Acquisition and Control Unit

Fig. 2 - Control system architecture.

This architecture permits to have an high availability, through self diagnostics and automatic fault detection, and an improved life cycle cost, deriving from reduced installation and maintenance costs [3].

A subsequent step in the direction of an higher efficiency and optimisation of plants, is to have a control system with the ability of saving the knowledge and heuristics accumulated from the past. One of the main aspects in substation automation and control is an expedient return-to-service following a system failure, so during the restoration from a fault, fast and correct operations are required. Actually, only the knowledge accumulated by the old experienced operators permits to face severe fault conditions. Thus, to preserve this ability also after their retirement, it is desired to develop an operation and maintenance system able to support the operators to do their tasks in shorter time and easier [4]. This ability can be performed only by new control systems based on expert system and/or fuzzy logic and/or neural network techniques. They have some functional characteristics able to simplify the operation and maintenance activity, as:

- ability to preserve the knowledge and heuristics accumulated from the past;
- ability to enlarge the base of knowledge easily.

This characteristics permits to obtain such advantages as quick restoration, relieving operators from the stress, reduction of manpower for routine operations, higher safety in restoration actions, higher diagnostic level, etc. .

A possible schematic software configuration for the control system expert system based for operation and maintenance of substations [4] is showed in fig. 3.

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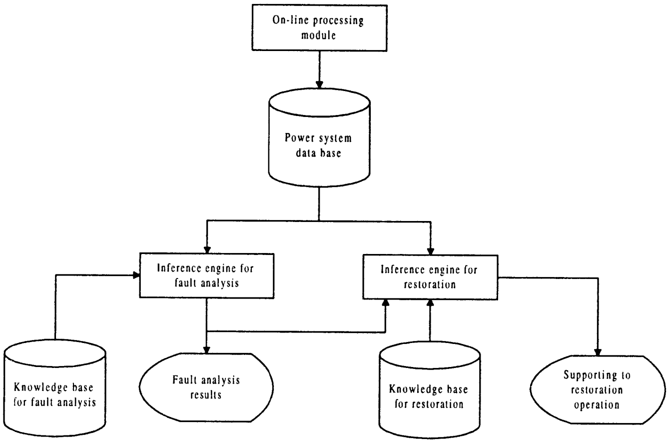

Fig. 3 - Schematic software configuration.

4 Substation safety

The automation of substation can be implemented by using commercially available smart Remote Terminal Units (RTUs), Programmable Logic Controllers (PLCs) and other logic circuit at extremely low costs. But, the adoption of these electronic equipments point out the importance of the safety concept. It is necessary to know the exact equipment behaviour in presence of internal misoperation or external disturbance in order to improve safety and efficiency of substation operation, particularly under severe contingency conditions.

It is vital that the hardware and software part of the RTUs, PLCs and other components are tested using built-in self-tests, by which the internal or external misoperation that may cause inaccurate actions of the automation systems are signalised.

The critical alarms to be implemented in substation are:

- transformer: hot spot alarm, loss of cooling, oil level, partial discharge, dissolved gas in oil, operating condition of on-load or no-voltage tap changer;
- open phase alarm;
- battery trouble.

This malfunctions are controlled by specific self-tests and in case of important malfunctioning all remote automated functions are locked [2].

However, as the substation diagnosis protection problems can be very time consuming and costly process, it often involves the review of hundreds of pages of recorder reports, it appears extremely suitable to have at disposal a diagnostic system which analyses records automatically from digital event recorders, finding the incorrect operations and identifying the source of the problems.

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5 Substation availability and maintenance

It is noted as the traction systems require an higher reliability and availability to guarantee the security for humans and safety for plants. These requisite must be taken into account both during the design of the automatic system architecture and during the particular equipment choice.
To example, the choice of the communication network topology may influence the reliability and availability indices of the system, therefore the substations must be connected with the control center by more communication lines, as showed in fig. 4, and with communication protocols using protected codes.

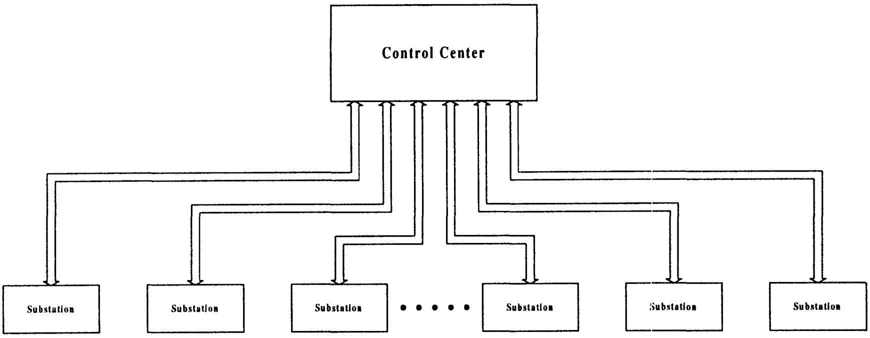

Fig. 4 - Conventional communication architecture

Relatively to adopted components and equipments, it is important to observe that without a continuous monitoring it is not possible to know the real availability of an electromechanical relay or scheme, it must occur the adopted relay packages are equipped of self-monitoring features to improve the knowledge of system availability and reduce troubleshooting times by identifying failures.
Then, in order to speed-up substation performance, increase the capacity and extend the life of existing equipment a more cost-effective approach to substation maintenance and operation must be adopted. Among the various systems and equipments particular interesting ones are:

- the transformer condition monitoring by a fault gas analyser, which permits to improve life and to predict the overload capability of the transformers, sensing the presence of the chemical trace of some elements (H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO and CO_2) in the transformer oil. Today, it is also possible to interface the fault gas analyser with the mentioned expert system which interprets the informations received and take some protective actions [4];
- the SF6 breaker diagnosis via SF6 analysis. In practice, it is possible to correlate the concentration of impurities with the breaker health, referring to its operating history. This provides a predictive

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maintenance tool [4];

- the substitution of the conventional protective relay with digital ones. This new kind of relay permit to execute self diagnostic and monitoring programs [5].

This preventive maintenance approach permits both to improve the availability of components, finding an anomaly of a monitored equipment before it leads to a fatal fault, and to reduce the manpower for plant maintenance, using equipment with self-monitoring features, with obvious improvement of the quantifiable and unquantifiable economical benefit

6 Communication architectures for traction system

The adoption of automation in traction substation requires suitable communication architectures. This consideration comes out still clearer if some electric conditions, typical of transportation systems, such as remote faults or overload currents are considered.

Relatively to the remote fault detection, it must be observed that its undoubted detection in DC electric traction plants is extremely difficult. Such a difficulty derive from the presence of long contact wires, which are also subjected to high overload, up to 3 times the rating power. These circumstances produce a strong reduction of fault current, which in such a case can be lower than the overload current.

A further worsening of the conditions may be represented by the presence of an equipotential mesh, which can cause both a further reduction and a profile change of the fault current.

Therefore, the choice of the substation feeding current, as sensing element in fault detection, not always may guarantee the breakers change over, so in some cases it must be forced to measure quantity different from current and to modify the traditional protective philosophies. Further informations, in general relative to the plant outside the substations and in the most cases of a not electric nature are required.

Such a kind of event, moreover typical of traction systems, can be easily modelled and managed with the automatic techniques previous exposed. They permit to integrate the information relative to current and voltage of the substation both with digital signals coming from digital relays, located in the middle and at the end of the line, and with such informations relative to the system operating state as number of trains, trains running mode, trains current, etc. . So, from the knowledge of the whole system a faster fault current detection is possible, locking the high-speed circuit-breakers to avoid further electric straining to the various equipments.

At the same way, it is possible to distinguish between a fault current and an overload one, coupling to the signals coming from the rate of change of slope relays that one relative to the presence of trains on the track section, affected by overcurrent. It will permit to avoid the untimely high-speed circuit-breakers trip, due to example to the speed passing of the traction load from a breaker to another, obtaining a strong reduction of the number of faults per year.

A further advantage directly reachable is to limit, with fast interventions, the faults propagation, so it is possible to delimit the plant area affected by severe fault conditions, making possible to continue the operation on the remaining areas.

All this considerations make possible to rearrange the architecture of fig. 4, obtaining a new control system communication architecture illustrated diagramatically in fig. 5.

This architecture shows that for every system area a substation is chosen as a *local control center*. This local control center accepts data both from the control center and from other adjacent substations, giving to the system the possibility to perform in an autonomous manner the critical control and protection functions speeding up the local responses [6,7]. The integration of the informations coming from the system data base with those ones coming from the adjacent substation can permit the undoubted identification of the faults and of their nature.

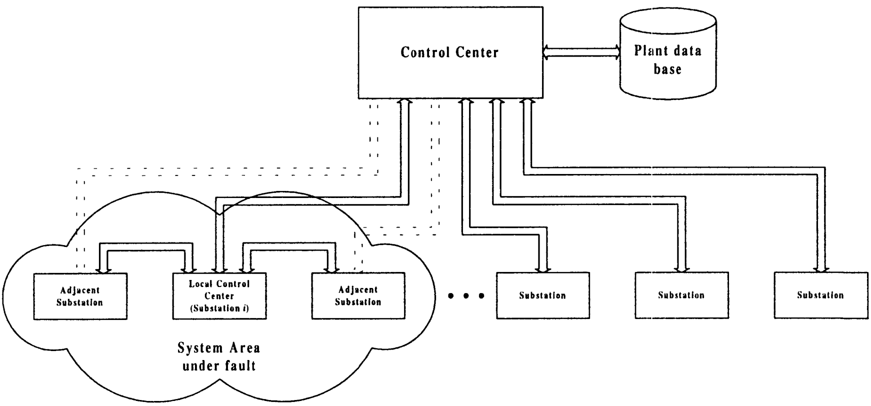

Fig. 5 - Control system communication architecture under fault.

In the proposed architecture, it is interesting to note that the master station, or the local control center equivalently, is configured dinamically depending on the particular fault condition, and when it is activated all the adjacent substations can talk with the control center only through it. This prevents any system violation, at every instant of time a substation can not perform any action if this one contradict the control or protective actions performed by the actual control center. Moreover, in order to guarantee an higher security level, in any instant of time the operator in the control center can switch the control system in a *manual mode* to face unexpected severe emergency operating conditions.

7 Cost/Benefit analysis

Relatively to the main quantifiable potential economic benefit of a substation automation system, it is possible to say that they are classifiable in two major categories as follows:

- reduction in capital expenditures;
- reduction in operating and maintenance costs.

On the other side, while the reduction in capital expenditures can be analysed only if specific planning studies are conducted for the site in question, the reduction in operating and maintenance costs can be evaluated by using simply equations that compute, on the base of historical statistics, costs of the non-automated substation which may be reduced when the corresponding substation automation functions are implemented. From experiences on small transportation system, the substation automation is justified on the basis of the operating and maintenance savings [8].

Relatively to unquantifiable benefits it is important to point out that the introduction of automation may improve the security of passengers and manpower, the reliability and availability of the system, and the customers satisfaction [8].

7 Conclusions

This paper has shown how the automation of traction substations can increase the reliability and availability of the whole electric power system. The main control and protection functions at substation level have been pointed out and a possible integrated control system architecture has been indicated. Also the contribution of such new control techniques as artificial neural network, expert system and fuzzy system in the system restoration or fault management has been discussed. In the latter part of the paper the possibility to demand some functions or applications from the control center to the substation local control center is showed.
All solutions described above have showed that

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