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Original Paper

Automatic Visualization of Single-Phase and Two-Phase Faults through a System of Two IPRs 240 with Signalling

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Abstract: *This paper is devoted to the automatic management of a type of fault (One or two broken phases) occurring on an electrical power transmission line. This line allows the transmission of the power flow from the affected phase to those which are in normal condition. Even if the line is affected by permanent single-phase or two-phase contingencies, the proposed automatic system supplies the receiver side with a few percentages of the nominal power, permanently maintaining the balanced nature of the three-phase power supply to the load. The transmission of information, fault alert affecting the line, to a few enlisted operators is carried out in real time by sending messages directly to their mobile phones or to their e-mail addresses followed by the sound alarm and the illumination of the relevant LEDs. The interest of this work then constitutes a significant and innovative solution for environments with high short-circuit levels on electrical energy transmission networks and contributes to their operating flexibility, even their reliability. The PLC (Programmable Logic Controller) associated with the communication module, modelled, consists of a series of standard logic gates of NOT, AND and OR operators. It has been implemented in the Zelio Soft2 software. The results obtained from the simulation show the reliability and the maintainability of the type 240 interphase power regulators (IPR) in solving the problems of power flow and signalling.*

Keywords: *Automatic visualization, IPR 240, Contingency, Short-circuits, One-Broken phase, Two-broken Phases, Interphase Power Regulator, Signalling.*

I. INTRODUCTION

For several years, operators in the electrical energy sector have been striving to improve its quality. The first efforts focused on continuity of service, then on compensation technology using FACTS systems to make access to energy in the user [1, 2]. However, there is a steady increase in demand from users, current unbalance and harmonic rates, and significant reactive power consumption [1]. The circulation of these same disturbed currents will also cause voltage imbalances and harmonics, which will be superimposed on the nominal voltage of the electrical network. In addition, incidents such as lightning strikes, short circuits or a sudden start of a machine rotating at high power can cause a sudden and significant drop in voltage [1]. Of course, these disturbances have harmful consequences on the electrical equipment, which can range from strong overheating or a sudden stoppage of the rotating machines to their total destruction [1]. Several solutions for depolluting electrical networks have already been proposed to improve the quality of the power flowing through the network, in other words to improve the flow of electrical power [3]. Those which best meet the industrial constraints in terms of fault management on an electrical power transmission line and which will be the subject of our investigations by means of a system of two interphase power regulators [3, 4, 5]. Because excessively high short-circuit levels are a widespread problem that have hardly been taken into account in the development of FACTS systems [6, 7]. The technique of managing a short-circuit by the dual power regulator system proves to be a reliable and profitable solution [6, 7]. Further, there are two kinds of IPRs known as synchronous IPRs and asynchronous IPRs. The synchronous IPRs have two branches and asynchronous one present more than two branches [8].

Thus, several researchers published in this field have attracted interest to exploit a power grid using IPRs [9, 10]. The goal of this study is to automatically manage the faults (One or two-broken phases) coming from a strong contingency on the electrical energy transport networks. Our investigation therefore aims to propose a technique for relieving certain short-circuits that are too high by using two IPRs controlled with combinatorial logic.

The paper is organized as follows. In Sec.2, we present the model of 240 IPRs associated with the model of the transmission line, the table of variables, the table of truth, the mathematical model of control law for PLC and the PLC flowchart. In Sec. 3, we present the different simulations for single phase fault or two-phase faults on Simulink and Zelio soft2 softwares. We conclude in Sec.4.

II. METHODOLOGY AND MODEL

A. The Model

As part of our work, we used two 240 IPRs, six intelligent circuit breakers, three of which are placed upstream and three downstream of the transmission line. They are controlled by a PLC associated with the communication module and the Zelio soft2 software.

a) The Interphase Power Regulator

The IPR uses a group of three-phase inductors and capacitors each installed in series between two networks or sub-networks. Those sets are new classes of equipment from other series compensation equipment connected to the networks. For example, phase A inductor and capacitor of the first network could be connected to phases B and C of the network [1, 3]. When all the components are energized, the amplitude and the phase angle (δ) of the current are defined in one of the two buses to which the regulator is connected. Current control thus allows the power carried by the controller to be regulated, as well as the reactive power absorbed or generated at one of the buses. Inductors and capacitors are always considered perfect without losses. The impedances of the series components are then reduced to their imaginary part (reactance). In the context of the regulator where the series components are arranged in parallel with respect to the others, the term susceptance is used instead of reactance for practical reasons [1, 3].

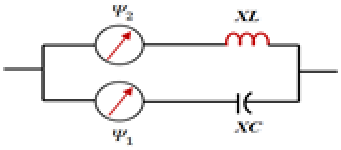

Figure1: IPR Connected between Two Networks or Subnets *[1].*

Depending on the connected bar, there are two types of IPRs known as synchronous IPRs and asynchronous IPRs. The IPR uses in this investigation is synchronous with two branches [1,4,11].

b) The 240 IPR

The IPR of figure 2 shows two phase susceptances which are connected to a set of switches which allow reversing the direction of the flow of active power P [12]. Active power P is defined as positive when flow occurs from the S side (sending) to the R side (receiving) [1, 12, 13]. The reactive powers are positive when the IPR generates reactive power on the buses to which it is connected. The susceptances B_1 and B_2 are connected to the voltage points, respectively. The reversal of the energy flow is simply done by reconnecting the susceptances on the S side so that B_1 takes the position of B_2 and vice versa $Q_s Q_r \underline{V}_{CS}\ \underline{V}_{BS}$[4]. This method of reversing the direction of energy flow is used for all IPRs. This IPR is designated as type 240 because the susceptances B_1 and B_2 are respectively connected to the voltage of the points $\underline{V}_{CS}$ *and* $\underline{V}_{BS}$ which are out of phase by an angle γ of 240 [1, 4, 12].

$$\begin{cases}\varphi_1 = -120^\circ \\ \varphi_2 = 120^\circ\end{cases} \qquad \gamma = \varphi_2 - \varphi_1 \qquad (1)$$

We notice using the expression (1) that the value of the angle $\gamma = 240^\circ$ hence the name 240 IPR. The phase current $\underline{I}_{Ar}$, is equal to the sum of the currents $\underline{I}_{B1}$, and $\underline{I}_{B2}$ in the susceptances of the direction of the flow of active power.

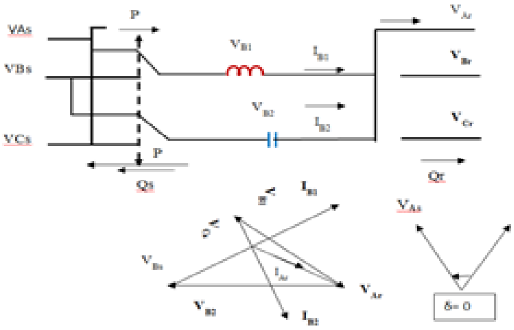

Figure 2: 240 IPR Equipped with Switches to Convert the Angle From-60° to +60° With Respect to Voltage *[1,21].*

c) Programmable logic controller

A programmable logic controller is a programmable electronic device intended for industrial processes by sequential processing. It sends information to pre-actuators (operative part) from input data (sensors: control part), instructions and computer program. The PLC can manage several type of information. Among them we have analog or numerical data.

B. Methodology

The analytical method uses the synoptic diagram of the implementation plan of a dual system of 240 IPR with three branches produced by interphase connection associated with a transmission line of electrical energy [6, 7, 11]. We establish the mathematical models materializing the control laws of the access control list of the PLC from which a flowchart will be developed [14-16].

a) Principle of operation of the dual IPR system

Consider an alternating current transmission so the network consists of an S-IPR (source 240 IPR), a transmission line, an R-IPR (receiver 240 IPR), a set of upstream and downstream smart circuit breakers (D_1 and D_4 for phases A, D_2 and D_5 for phases B, D_3 and D_6 for phase 3), and a PLC [9, 10].

The discrete reactances of the source 240 IPR are controllable via the associated switches S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8 and S_9. Further, the similar set of switches S_1', S_2', S_3', S_4', S_5', S_6', S_7', S_8' and S_9' are associated with the reactors of the receiver 240 IPR. Therefore, there are eighteen switching reactors to be managed overtime in normal and unplanned modes of power flow through the transmission line, while maintaining synchronism between the two 240 IPRs [9, 10].

Any phase of the power transmission line which is infected by a high risk, for example a short circuit, must be deactivated by the associated circuit breakers and the flows are redirected on the phases in normal state by the command of the PLC. Thanks to the communication module associated with the PLC through the configuration of the SR2COM01 communication interface, certain technicians will be kept informed in real time of any contingency that will affect the line in an unforeseen situation. This will allow them to intervene if the fault persists [9, 10].

The novelty brought by the double 240 IPR topology is that, even in high-level situations, for example, a single-phase or even two-phase short circuit, the receiving 240 IPR with three branches, can continuously supply three phase feeds to the receiving terminal from any working phase. Thus, the PLC to be modelled is a new tool endowed with great relevance for a better management of the power flow, in alternating current power supply networks under a double topology IPR as seen in Figs. (3) [8, 17, 18].

Initially, it is important to identify the input and output variables to be managed by the access control list of the dual 240 IPR system. The analysis of the information observed in Figs. (3) leads to the main input and output variables summarized in the Table 1 (see appendix 2).

It is also important to master the main operations and commands of the system to be processed. This is because under normal operating conditions (no contingencies) all peripheral switching commands must be initially enabled, in which case the 240 IPR's dual system behaves as a power transmission without loss. If a high level fault occurs on phase A (single phase short circuit for example), then the smart circuit breakers D_1 and D_4 would automatically switch off phase A. The information can be captured by the access control list from the state of d_1 and d_4, to be able to pass to a necessary closure of reactances (Xaas, Xbas, Xcas, Xbbs, Xccs) and (Xaar, Xaar, Xbbr, Xacr, Xccr) as seen in table 2 (see appendix 2).

b) Control laws of PRL

According to Table 2, it is easy to define each output variable Sj (j = 1, 2, ..., 9) as a raw function of the combined input variables as follows [14,15]:

$$\mathrm{S}_1 = \bar{\mathrm{d}}_{36}\mathrm{d}_{25}\mathrm{d}_{14} + \mathrm{d}_{36}\bar{\mathrm{d}}_{25}\mathrm{d}_{14} + \mathrm{d}_{36}\mathrm{d}_{25}\bar{\mathrm{d}}_{14} + \mathrm{d}_{36}\mathrm{d}_{25}\mathrm{d}_{14} + \bar{\mathrm{d}}_{36}\bar{\mathrm{d}}_{25}\mathrm{d}_{14} \quad (2)$$

$$\mathrm{S}_2 = \mathrm{d}_{36}\mathrm{d}_{25}\bar{\mathrm{d}}_{14} + \mathrm{d}_{36}\mathrm{d}_{25}\mathrm{d}_{14} + \bar{\mathrm{d}}_{36}\bar{\mathrm{d}}_{25}\mathrm{d}_{14} \quad (3)$$

$$\mathrm{S}_3 = \mathrm{d}_{36}\mathrm{d}_{25}\bar{\mathrm{d}}_{14} + \mathrm{d}_{36}\mathrm{d}_{25}\mathrm{d}_{14} + \bar{\mathrm{d}}_{36}\bar{\mathrm{d}}_{25}\mathrm{d}_{14} \quad (4)$$

$$\mathrm{S}_4 = \mathrm{d}_{36}\bar{\mathrm{d}}_{25}\mathrm{d}_{14} + \mathrm{d}_{36}\mathrm{d}_{25}\mathrm{d}_{14} + \bar{\mathrm{d}}_{36}\mathrm{d}_{25}\bar{\mathrm{d}}_{14} \quad (5)$$

$$\mathrm{S}_5 = \bar{\mathrm{d}}_{36}\mathrm{d}_{25}\mathrm{d}_{14} + \mathrm{d}_{36}\bar{\mathrm{d}}_{25}\mathrm{d}_{14} + \mathrm{d}_{36}\mathrm{d}_{25}\bar{\mathrm{d}}_{14} + \mathrm{d}_{36}\mathrm{d}_{25}\mathrm{d}_{14} + \bar{\mathrm{d}}_{36}\mathrm{d}_{25}\bar{\mathrm{d}}_{14} \quad (6)$$

$$S_6 = d_{36}\bar{d}_{25}d_{14} + d_{36}d_{25}d_{14} + \bar{d}_{36}d_{25}\bar{d}_{14} \quad (7)$$

$$S_7 = \bar{d}_{36}d_{25}d_{14} + d_{36}d_{25}d_{14} + d_{36}\bar{d}_{25}\bar{d}_{14} \quad (8)$$

$$S_8 = \bar{d}_{36}d_{25}d_{14} + d_{36}d_{25}d_{14} + d_{36}\bar{d}_{25}\bar{d}_{14} \quad (9)$$

$$S_9 = \bar{d}_{36}d_{25}d_{14} + d_{36}\bar{d}_{25}d_{14} + d_{36}d_{25}\bar{d}_{14} + d_{36}d_{25}d_{14} + d_{36}\bar{d}_{25}\bar{d}_{14} \quad (10)$$

We define a new combined variable:
$S_{10} = \bar{d}_{36}d_{25}d_{14} + d_{36}\bar{d}_{25}d_{14} + d_{36}d_{25}\bar{d}_{14} + d_{36}d_{25}d_{14}$(11)

Then, the simplified expressions of the equations can be written as follows [14, 15]:
$S_1 = S_{10} + \bar{d}_{36}\bar{d}_{25}d_{14}$ (12)
$S_2 = d_{36}d_{25} + \bar{d}_{36}\bar{d}_{25}d_{14}$ (13)
$S_3 = S_2$ (14)
$S_4 = d_{36}d_{14} + d_{36}d_{14} + \bar{d}_{36}d_{25}\bar{d}_{14}$ (15)
$S_5 = S_{10} + \bar{d}_{36}d_{25}\bar{d}_{14}$ (16)
$s_6 = S_4$ (17)
$S_7 = d_{25}d_{14} + d_{36}\bar{d}_{25}\bar{d}_{14}$ (18)
$s_8 = s_7$ (19)
$S_9 = S_{10} + d_{36}\bar{d}_{25}\bar{d}_{14}$ (20)
$L_1 = \bar{d}_{14}$ (21)
$L_2 = \bar{d}_{25}$ (22)
$L_3 = \bar{d}_{36}$ (23)
$A = \bar{d}_{14} + + \bar{d}_{25}\bar{d}_{36}$ (24)
The set of Eqs. (13) -(24) analytically represents the fundamental principles of PLC for a dual 240 IPR system [14, 15].

c) Logic diagram of a PLC of the transport network with two IPRs

Figure (5) (see appendix 3) schematically illustrates the access control list flowchart for a dual 240 IPR system within an alternate power transmission network. 240 IPR novelty is based on the capabilities to automatically maintain a balanced AC power supply to the receiver, even under degraded operating conditions due to the loss of one or more two phases of the transmission line. The architectural core of the access control list is built using logic gates of OR, AND, and NOT standards from the mathematical models due to the above equations [14, 15].

III. RESULTS AND DISCUSSIONS

The simulation that we are going to perform with the MATLAB/SIMULINK and Zelio Soft2 softwares will be done in three stages. We first suppose that the lines are without faults, then a fault on one phase and finally two phases with faults.

A. Modelling for simulation

We propose in this part to simulate the PLC with or without faults on the line. We will proceed initially to simulate the PLC without fault on the line. Then, the case where the fault occurs on it, in particular phase A with a contingency over an interval of 10 time units and phases B and C with simultaneous two-phase faults over an interval of 4 to 6 time units. Finally, with non-simultaneous two-phase faults which respectively affected phase A over an interval of 2 to 8 time units and phase B from 7 to 8 time units.

B. PLC simulation: without fault on the line

All the input signals d_1, d_2, d_3, d_4, d_5, d_6 are at state 1 as shown in fig. (7) that explains why all the states of the circuit breakers are in the ON position. This reflects the absence of fault on the line. The simulated result for this condition is shown in Figs. (7), (8) and (9).

Figure (8) shows the reactance states when there is no fault on the line. Moreover, when the line has no fault, all the input signals are at state 1 and all the reactance states S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8 and S_9 which are the signals of output, are at 1, justifying that the line is without contingencies. Therefore the input signals $d_{14} = d_{25} = d_{36} = 1$.

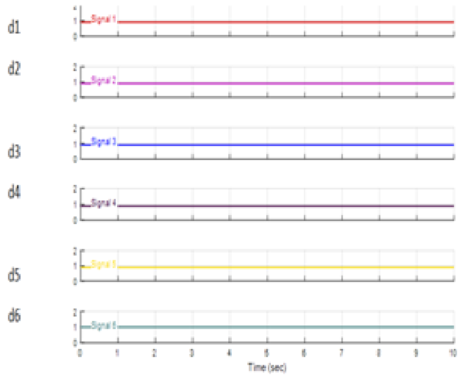

Figure 7: Parameterized Signal Builder: No Fault on the Line

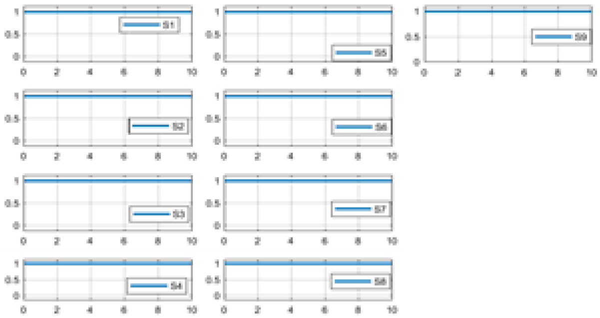

Figure 8: States of Reactances without Fault on the Line

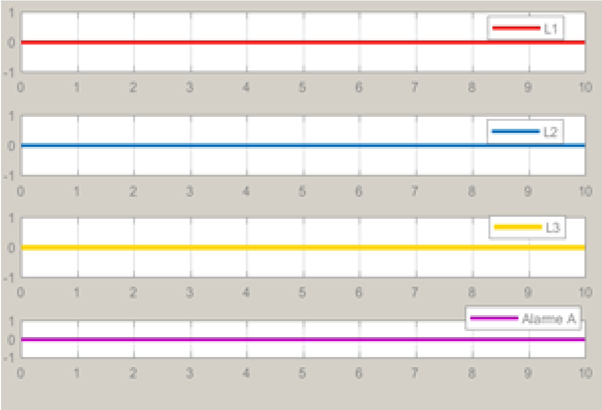

Figure 9: States of LEDs and Audible Alarm without Fault on the Line

Figure (9) shows that none of the LEDs L_1, L_2, L_3, nor alarm A is activated to signal the fault on the line, this is justified by their states which are all at 0. Consequently, the operators will not receive any message on mobile telephones or e-mail addresses indicating the fault on the line.

Figure (10) (see appendix 10) is the result of the simulation performed by the Zelio Soft2 software. It illustrates Figs. (10), (11) and (12) highlight the real-time operation of the PLC. We note that all these results are consistent with what is predicted in the truth table. We can therefore conclude that the expected results are almost 100% satisfactory.

a) PLC Simulation with Fault on Phase A (Broken Phase)

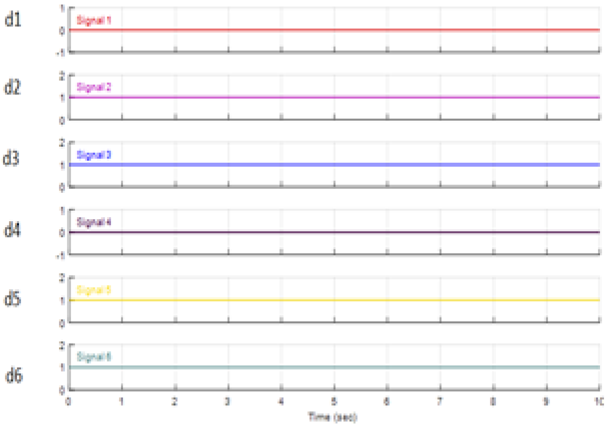

Figure 11: Configured Signal Builder: with Fault on Phase A

Figure (11) shows the input signals configured with fault on phase A over ten time units. Thus, the signals d_1 and d_4 are at state 0, so a contingency has occurred on phase A and the circuit breakers D_1 and D_4 have de-energized this phase. The other input signals d_2, d_3, d_5, d_6 are at state 1. This situation means that phases B and C are under normal conditions corresponding to $d_{25} = d_{36} = 1$ and $d_{14} = 0$. After the simulation, the output signals S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8 and S_9 which are only states of the reactances and L_1, L_2, L_3, A respectively the states of the LEDs accompanied by audible alarm. This provides real-time information related to phases A, B and C of the line and shown in Figs. (13) and (14).

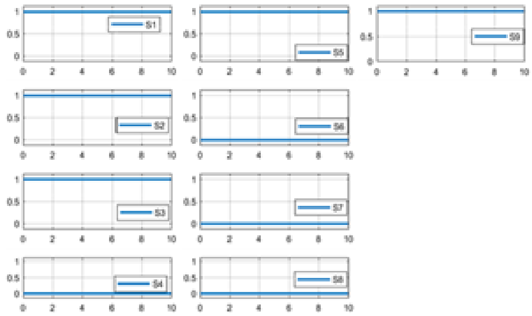

Figure 12: ***States of Reactances with Fault on phase A***

Figure (12) shows the states of reactors S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8 and S_9 with contingency on phase A. When a fault affects phase A over ten time units, circuit breakers D_1 and D_4 open and de-energize that affected line. The PLC automatically switches the reactances S_1, S_2, S_3, S_5 and S_9 to the ON position to redirect the energy flows from the affected phase to the other two without contingency on the source side and redistribute on the three phases on the side receiver. The other states of reactances S_4, S_6, S_7, S_8 considered useless are switched to the OFF position.

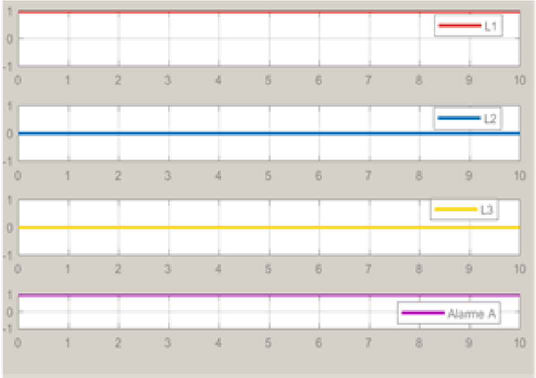

Figure 13: LED States and Audible Alarm

Figure (13) shows the states of LEDs L_1, L_2, L_3 and alarm A which indicate the behavior of phases A, B and C. In addition, $L_1 = A = 1$ and $L_2 = L_3 = 0$, this means that the LED L_1 and the alarm are activated to signify the contingency which affected phase A. Otherwise, the message “Phase fault alert A, $d_1d_4 = 0$” will be transmitted to the operators from mobile phones or on e_mail addresses, to keep them informed in real time of the contingency on phase A.

Figure (14) (see appendix 4) shows the states of the reactors, LEDs and alarm with fault on phase A, simulated by the Zelio Soft2 software. This result illustrates those presented in Figs. (12) and (13). It can be seen that the results obtained by Matlab are identical to those presented from Zelio Soft2 software and materialize the results predicted in the truth table (see Table 2 in appendix 2). We can also say that these results obtained are 100% satisfactory.

b) PLC simulation with simultaneous two faults affecting B and C (short-circuits)

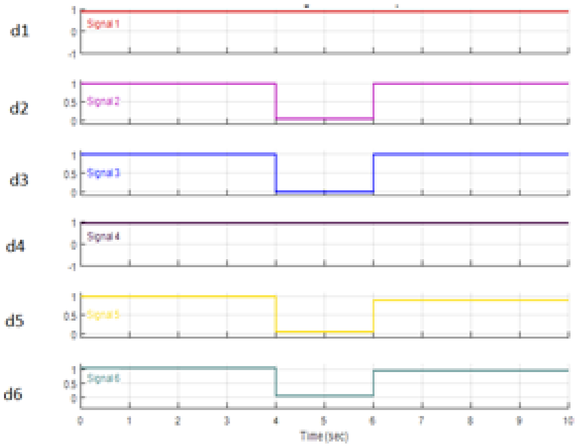

Figure 15: Parameterized Signal Builder with Simultaneous Two-phase Faults Affecting Phases B and C.

Figure (15) shows the input signals configured with simultaneous two-phase faults affecting phases B and C over an interval of 4 to 6 time units. Moreover, during this disturbance period, the input signals d_1 and d_4 are at state 1, so $d_{14} = 1$ proving that phase A is not affected and circuit breakers D_1 and D_4 are still in service. The other input signals d_2, d_3, d_5, d_6 are at state 0, this means that phases B and C are affected. The simulation results are shown in Figs. (15) and (16).

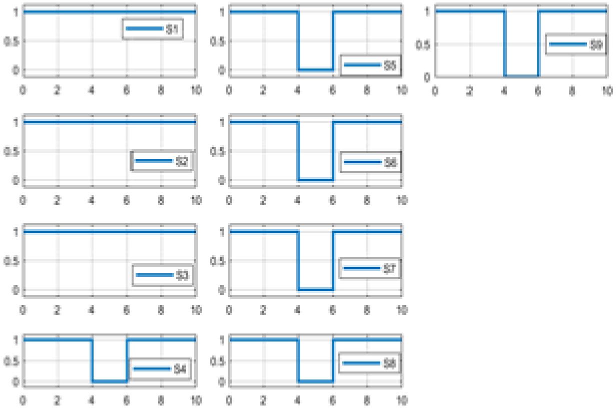

Figure 16: States of Reactances with Simultaneous Two-Phase Faults Affecting Phases B and C.

Figure (16) shows the states of reactances S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8 and S_9 with contingency on phases B and C. When a fault simultaneously affects phases B and C over an interval of 4 at 6 units of time, the circuit breakers D_2, D_5 and D_3, D_6 open and de-energize the affected phases B and C. The PLC automatically switches the reactances S_1, S_2, S_3 to the ON position during the contingency period to redirect the energy flows of the affected phases to phase A without contingency on the source side and redistribute to the three phases on the source side. The other reactances S_4, S_5 S_6, S_7, S_8 and S_9 considered useless are then switched to the OFF position. The predicted results in the truth table (Table 2) and those of this simulation are the same.

Figure 17: LED States and Audible Alarm

Figure (17) shows the states of LEDs L_1, L_2, L_3 and alarm A, which indicate the behavior of phases A, B and C. Moreover, $L_1 = 0$ and $L_2 = L_3 = A= 1$, this means that the LEDs L_2, L_3 and the alarm are activated to signify the contingency which affected phases B and C. consequently, the message “Phase fault alert B, $d_2d_5=0$; Phase fault alert V_S, $d_3d_6 = 0$” will be transmitted to the operators through mobile phones or e_mail address indicating the contingency on phase B and C.

Figure (18) (see appendix 5) shows the states of the reactances, indicator lights and alarm with simultaneous two-phase faults affecting phases B and C, resulting from the simulation by the Zelio Soft2 software. This result is similar to that previously presented in Fig. (14) and (15). It is clearly appeared that the results obtained from Matlab software are identical to those obtained from Zelio Soft2 software. This fact confirms the predicted results in the truth table (see Table 2 in Appendix 2). We can also say that these results obtained are still satisfactory.

c. PLC simulation with non-simultaneous two phase faults affecting A and B (short-circuits)

Figure (19) shows the input signals configured with non-simultaneous two-phase faults affecting phases A and B over an interval of 2 to 8 time units and 7 to 8 time units. Indeed, during a period of 2 to 8 units of time the contingency affected phase A, the input signals d_1 and d_4 are at state 0, that is to say $d_{14} = 0$ proving that this phase is affected and circuit breakers D_1 and D_4 open to de-energize the latter. The phase B is affected over a period of 7 to 8 units of time, which leads to the opening of circuit breakers D_2 and D_5. Input signals d_2, d_5, d_1 and d_4 are at state 0, which means that phases A and B are affected. The results of the simulation are shown in Figs. (20) and (21).

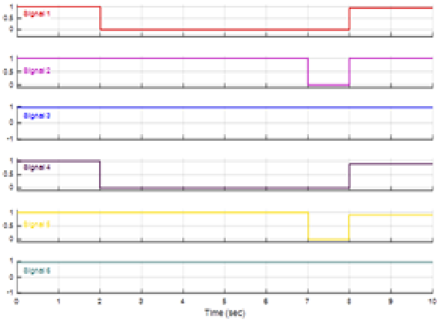

Figure 19: Builder Signal Configured with Non-Simultaneous Two-Phase Faults Affecting Phases A and B.

Figure (20) shows the states of reactances S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8 and S_9 with contingency on phases A and B. When two-phase faults affect phases A and B non-simultaneously over two different intervals from 2 to 8 time units for phase A and from 7 to 8 time units for B, the circuit breakers D_1, D_4 and D_2, D_5 respectively controlling phases A and B open and turn off the next state 0 the disturbance time on these phases. The PLC automatically switches the following reactances to the ON position: S_1, S_2, S_3 and S_5 during the contingency period of 2 to 7 time units; S7, S8 over the interval of 7 to 8 time units and S_9 during all contingency periods to redirect the energy flows from the affected phases to phase C, which is without contingency on the source side and redistribute on the three phases towards the receiver side. The other reactances S_4 and S_6 considered useless are switched to the OFF position.

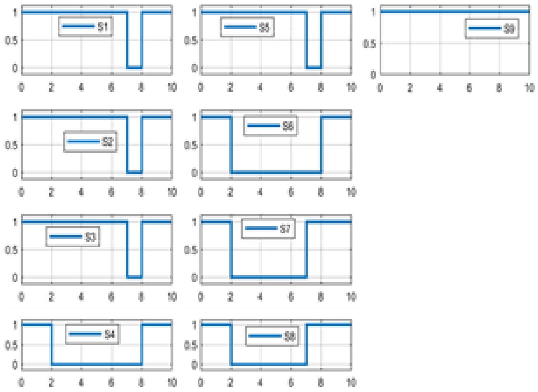

Figure 20: ***States of reactors with non-simultaneous two-phase faults affecting phases A and B.***

Figure (21) shows the states of LEDs L_1, L_2, L_3 and the alarm A which indicates the behaviour of phases A, B and C. Indeed, $L_1 = 1$, $L_2 = 1$, $A = 1$ depending on each one, the period of contingency and $L_3 = 0$, this means that LEDs L_1, L_2 and the alarm are activated to sign the contingency which affected phases A and B. Indeed, this message “Phase A fault alert, $d_1d_4 = 0$; phase B fault, $d_2d_5 = 0$” will be transmitted to the operators selected as recipients on their mobile phones or on their e-mail address indicating the contingency on phases A and B.

Figure 21: LED States and Alarm

C. Interpretation of results

The results obtained by the PLC simulation are shown in the precedent figures. Figure (6), (7), (8), (9), (10), (11) show some operating modes generated over ten time units with input bits d_1, d_2, d_3, d_4, d_5 and d_6. The combined input bits $d_{14} = d_1\ d_4$, $d_{25} = d_2\ d_5$ and $d_{36} = d_3\ d_6$ refer to the operating status of phase A, phase B and phase C respectively.

Figure (5) presents the faultless lines, so, $d_{14} = d_{25} = d_{36} = 1$. The results obtained and presented in figs. (6), (7) and (8) show that all the switches are in the "ON" position and no lights are on, even the alarm is in the “OFF” position. To this end, the operators cannot receive the SMS which tells them the fault position on the phases and this means that no contingency has affected the line. This result is acceptable because it exactly reflects the one predicted by the truth table (Table 2 in Appendix 2).

Figure (9) shows a single-phase fault (broken phase) which affected phase A over ten time units, which translates the positions $d_{14} = d_1\ d_4= 0$, $d_{25} = d_2d_5= 1$ and $d_{36} = d_3\ d_6= 1$ and the results obtained and presented at Figs. (11) and (12) show the position of the associated switches, over ten time units. Switches S_1, S_2, S_3, S_5 and S_9 are automatically switched to ON by the PLC and switches S_4, S_6, S_7, S_8 are switched to OFF considered as useless switches.

Figure (11) shows the status of the LEDs and the audible alarm. Thus, LED L_1 and the alarm are triggered to the fault signal on phase A over ten time units, as long as LEDs L_2 and L_3 are in the OFF position. In fact, thanks to the wireless communication module associated with the PLC, the operators whose telephone contacts and e-mail addresses were selected when configuring the communication interface will receive this message "Phase fault alert in phase A, $d_1d_4 = 0$” in real time. Figure (13) presents the simultaneous two-phase faults (two-phase short-circuits) which affected phase B and phase C over an interval of 4 to 6 time units justified by the positions of the input bits $d_{14} = d_1\ d_4 = 1$, $d_{25} = d_2d_5= 0$ and $d_{36} = d_3\ d_6= 0$. Then, the result presented in Figs. (14) and (6) shows that in the interval of 4 to 6 units of time, the switches S_1, S_2 and S_3 are automatically switched to ON by the PLC and the switches S_4, S_5, S_6, S_7, S_8, S_9 are switched to OFF and considered useless.

Figure (15) shows the status of the LEDs and the buzzer between 4 to 6 units of time. Thus LED L_2, L_3 and the alarm are activated to signal the fault respectively on phase B and phase C, as long as LED L_1 is in the OFF position, which confirms the absence of contingency on phase A. For this purpose, this message entitled “Phase B fault alert, $d_2d_5 = 0$; Phase C fault alert, $d_3d_6 = 0$” will be sent to the recipient operators whose contacts are configured using the communication interface associated with the PLC. The switches S_1, S_2 and S_3 are automatically switched to ON by the PLC and the switches S_4, S_5, S_6, S_7, S_8, S_9 are switched to OFF and considered useless.

Figure (19) presents the states of reactors S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8 and S_9 with non-simultaneous two-phase contingencies on phases A and B (short-circuit and broken phase). When non-simultaneous two-phase faults affect phases A and B over two different intervals of 2 to 8 time units for phase A and 7 to 8 time units for B, circuit breakers D_1, D_4 and D_2, D_5 respectively controlling phases A and B open and de-energize phases A and B according to the disturbance time on these phases. The PLC automatically switches the following reactances to the ON position: S_1, S_2, S_3 and S_5 during the contingency period of 2 to 7 time units; S_7, S_8 on the interval of 7 to 8 time units and S_9 during all the contingency periods to redirect the energy flows of the affected phases on phase C which is without contingency on the source side and redistribute on the three phases towards the side receiver. The other reactances S_4 and S_6 considered useless are switched to the OFF position.

Figure (19) shows the states of LEDs L_1, L_2, L_3 and alarm A which indicate the behaviour of phases A, B and C. Moreover, $L_1 = 1$, $L_2 = 1$, $A = 1$ depending on each one, the period of contingency and $L_3 = 0$, this means that LEDs L_1, L_2 and the alarm are activated to sign the contingency which affected phases A and B. The other reactances S_4 and S_6 considered useless are switched to the OFF position. Moreover, this message “Phase fault alert A, $d_1d_4=0$; Phase fault alert B, $d_2d_5 = 0$” will be transmitted to the operators selected as recipients on their mobile phones or on their e-mail address indicating the contingencies on phases A and B. For each mode of operation, the control signal of the switches S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9 correspond perfectly to the behaviour predicted in table 2 (see Appendix 2) of the truth table. Note that the results from the simulation using the Matlab software and those obtained using the Zelio Soft2 software are identical. We can therefore better appreciate this automatic technique of using a dual IPR system in fault management on power transmission lines.

IV. CONCLUSION

We have presented an automatic contribution of two IPRs system to improve the electrical energy compensation in a transmission network following short-circuit or phase loss problems. Even if the transmission line is affected by permanent single-phase (broken phase) or two-phase (two phase short-circuits) contingencies, the proposed automatic system provides the receiver side with a few percentages of the nominal power, always maintaining the balanced nature of the three-phase power supply of the charged. The signalling system installed would allow some maintenance workers to be informed in real time of any contingency that might occur on the line.

Appendix 1:

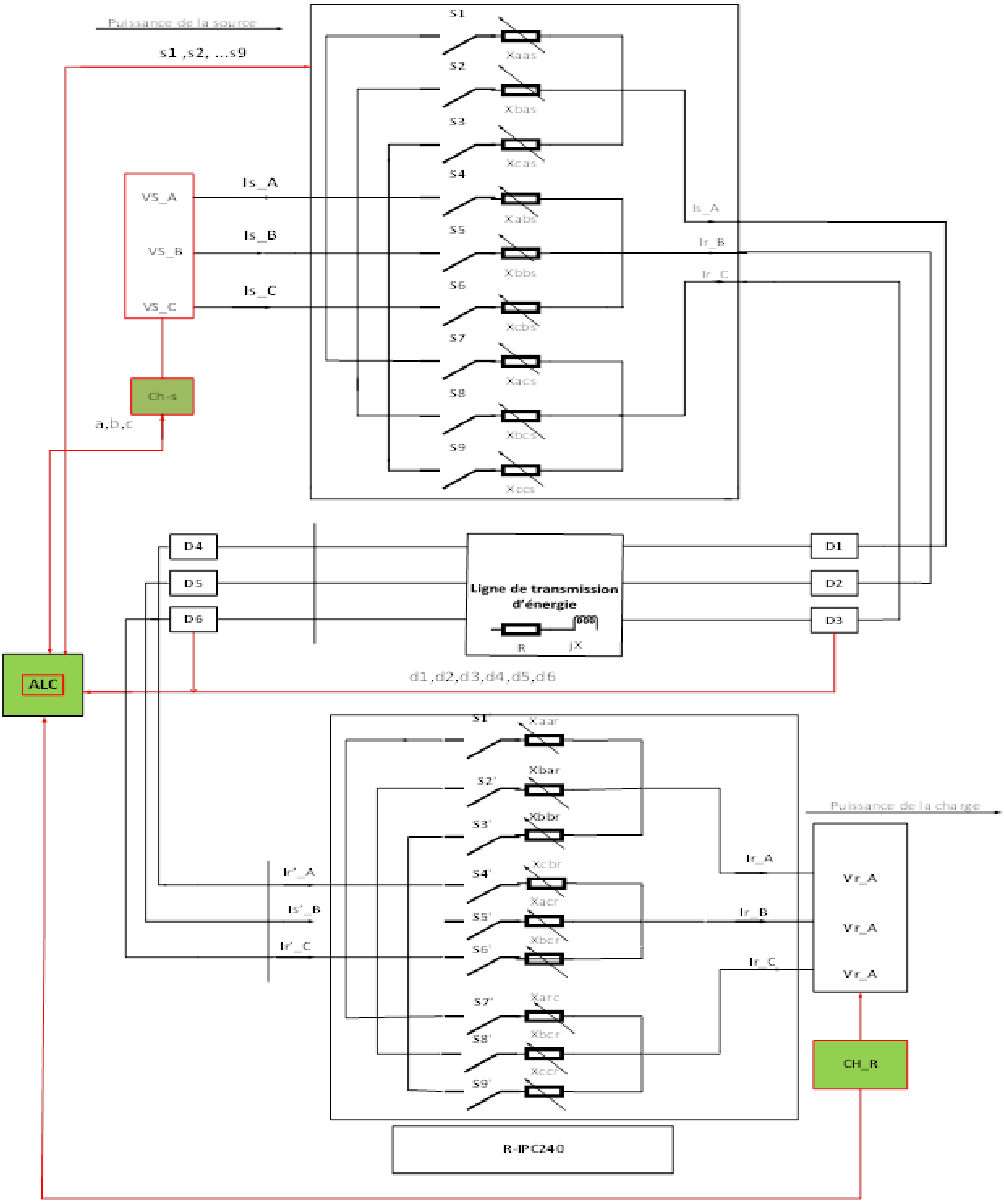

Figure 3: Electric Power Transmission Line Equipped with a Dual IPR 240 System[2]

Appendix 2:

Table 1: Description of Outputs and Inputs of the System

Symbols	Kinds	Descriptions
a, b, c, a', b' and c'	input	Information data for the load angle
d_1, d_2, d_3	input	State of circuit breakers open or closed (D_1, D_2, D_3 respectively)
d_4, d_5, d_6	input	State of circuit breakers open or closed (D_2, D_5, D_6 respectively)
i_1, i_2, i_3, i_4, i_5, i_6, i_7, i_8, i_9	input	Switch state open or closed (S_1,S_2,S_3,S_4,S_5,S_6,S_7,S_8,S_9 respectively)
S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9	output	Line reactor switching states associated with the S-IPC 240

L_1, L_2, L_3, A	output	The states of the LEDs and audible alarm
S1',S2',S3',S4',S5',S6',S7',S8',S9'	output	The line feedback switching states associated with the R-IPC 240

Table 2: ***PLC truth table***

Combined contingency detection marginal state inputs d1, d2, d3, d4, d5, d6			**Output variable and reactance to be switched**									**Transmission line power flow mode**	**Signaling**
d_{36}= $d_3.d_6$	**d_{25}= $d_2.d_5$**	**d_{14}= $d_1.d_4$**	**S1 S1'**	**S2 S2'**	**S3 S3'**	**S4 S4'**	**S5 S5'**	**S6 S6'**	**S7 S7'**	**S8 S8'**	**S9 S9'**		
Phase VS	**Phase B**	**Phase AT**	**Xaas Xaar**	**Xbas Xbar**	**Xcas Xcar**	**Xabs Xabr**	**Xbbs Xbbr**	**Xcbs Xcbr**	**Xacs Xacr**	**Xbcs Xbcr**	**Xccs Xccr**		
0	0	0	0	0	0	0	0	0	0	0	0	3-phase default	L_1= L_2=L_3 = A=1.
0	0	1	1	1	1	0	0	0	0	0	0	Fault in C and B	L_1 = 0 L_2=L_3=A=1.
0	1	0	0	0	0	1	1	1	0	0	0	Fault in A and C	L_1=L_3=A =1 L_2 = 0.
0	1	1	1	0	0	0	1	0	1	1	1	Fault in C	L_1= L_2= 0 L_3=A=1
1	0	0	0	0	0	0	0	0	1	1	1	Fault in A and B	L_1=L_2= A=1 L_3 = 0.
1	0	1	1	0	0	1	1	1	1	1	1	Fault in B	L_2=A=1 L_1=L_3= 0
1	1	0	1	1	1	0	1	0	0	0	1	Fault in A	L_1= A= 1 L_2=L_3= 0
1	1	1	1	1	1	1	1	1	1	1	1	No fault	L_1= A= 0 L_2= L_3 = 0

Appendix 3:

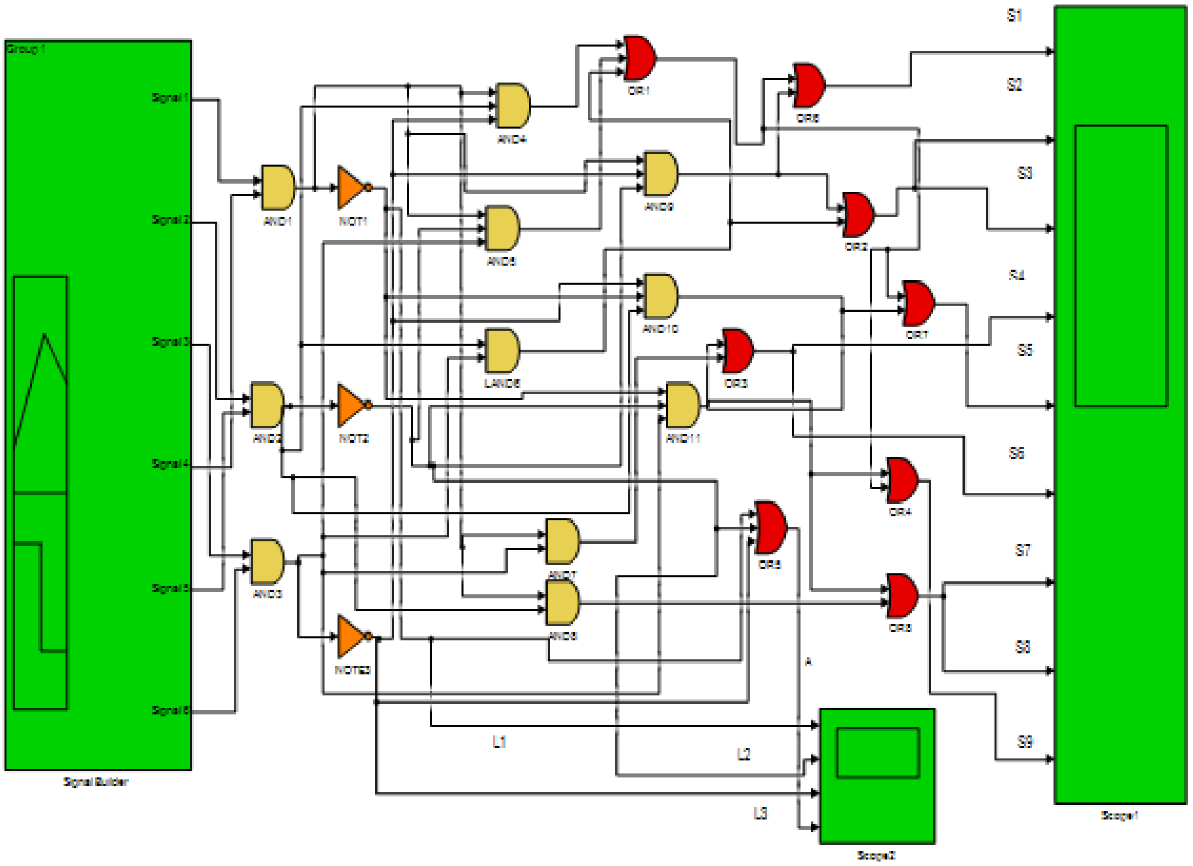

Figure 5: PLC Flowchart [14,15]

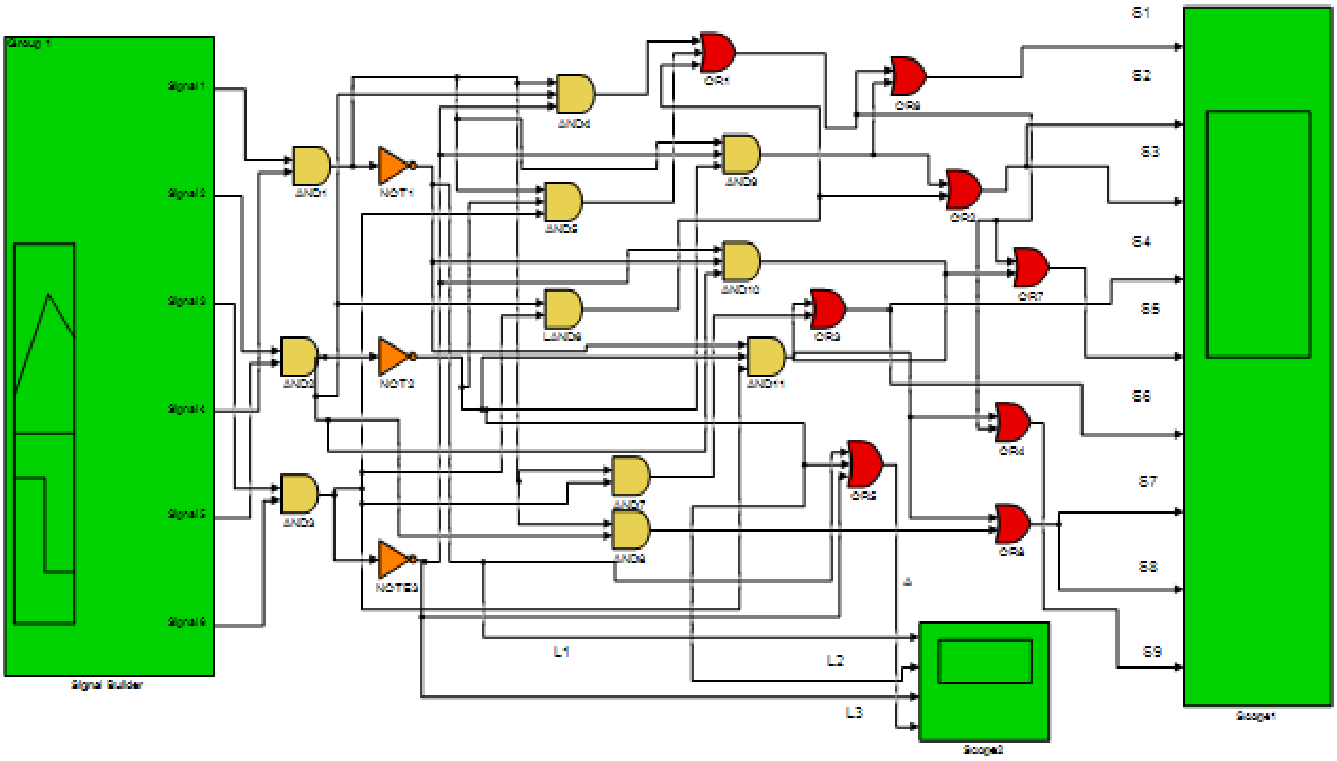

Figure 6: Logic Diagram of the Programmable Controller

Appendix 4

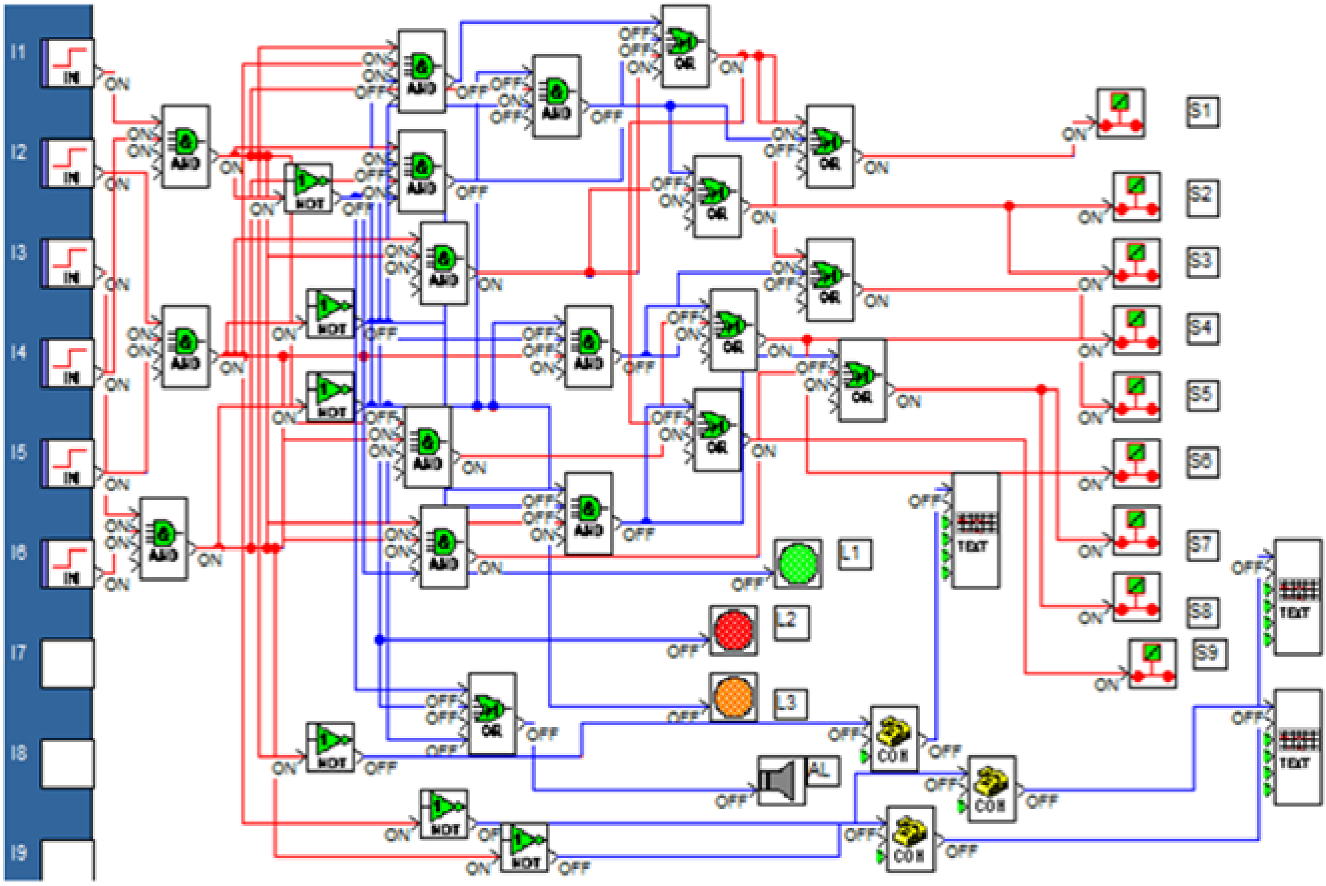

Figure 10: Illustration of Reactor, LED and Alarm States by Zelio Soft2: Case, No Fault on the Line

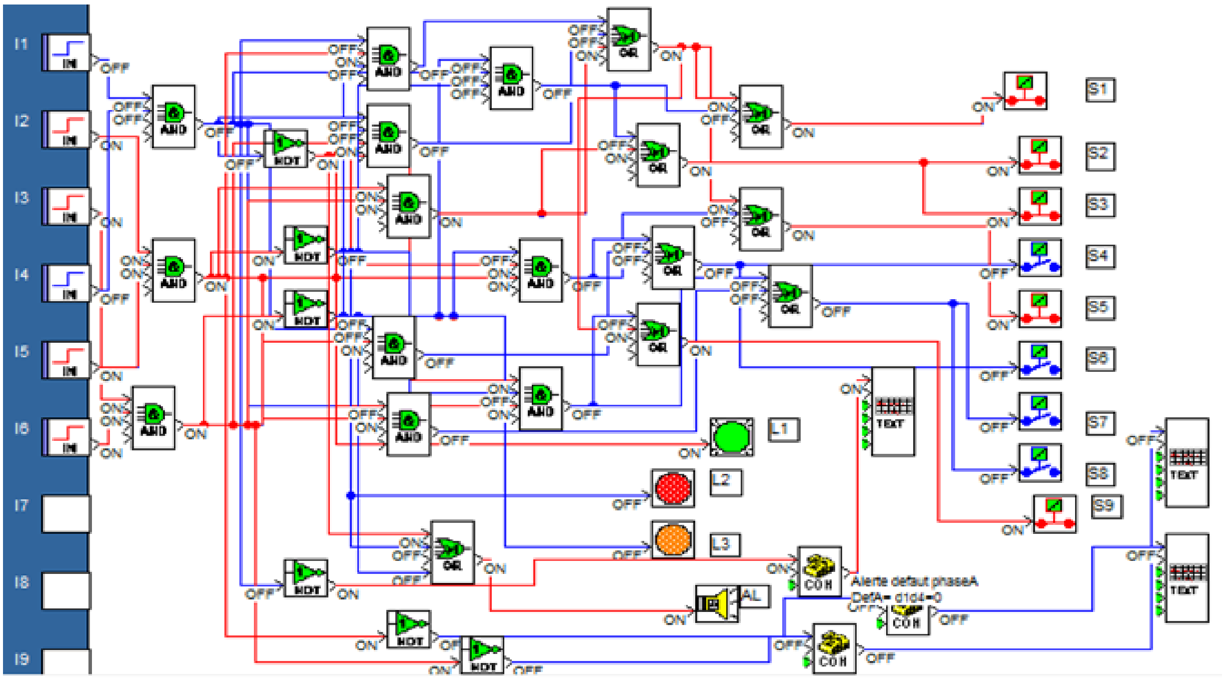

Figure 14: Illustration of the States of the Reactors, LEDs and Alarm with Fault on Phase A by Zelio Soft2

Appendix 5

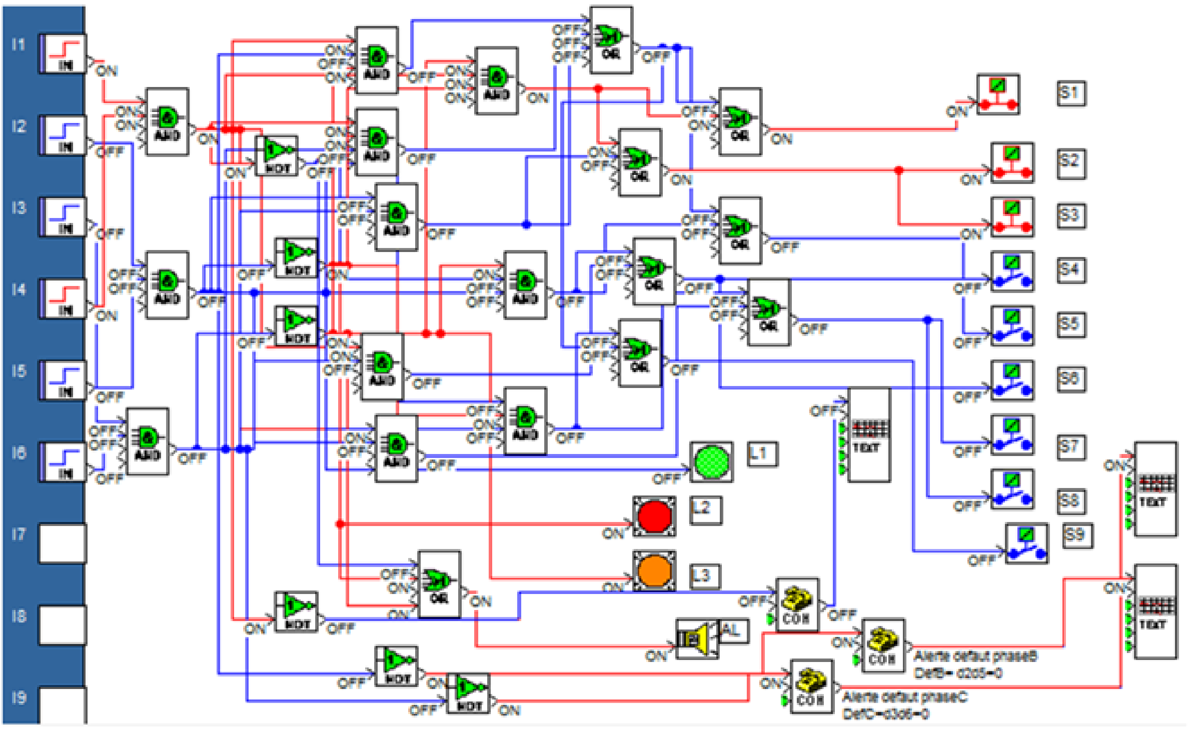

Figure 18: Illustration by Zelio Soft2 of the States of the Reactors, LEDs and Alarm with Simultaneous Two-Phase Faults Affecting Phases B and C

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