Determination of Protection and Relay Coordination Strategy in Electrical Power Systems Based on Renewable Energy Generation Resource Using Petri Net Method

Nihat PAMUK
Turkish Electricity Transmission Company, Sakarya, Turkey
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ABSTRACT

The principle of protection in electrical power system targets to determinate at timely of accruing faults and to isolate at the most appropriate time of the faulted sections of the power grid. This situation is realized through coordination among the protective devices. The involvement of renewable energy generation resources to the energy transmission system complicates the network protection, thus undermining the security coordination or decreasing the protection coordination zone. In particular, such issues become even more vigorous in power networks with effect of renewable energy resource generations. Therefore, the conventional power protection methods are insufficient in such networks, requiring software strategies involving the renewable energy generation resources. For that purpose in this study, Petri net method is used for estimating the faulted section in power transmission network in the presence of renewable energy generation resources and designing of protection coordination schemes. The information about the status of protection elements acquired from the automation system was adopted as input to the Petri net method. Renewable energy resource generations effect can increase the risk of disharmony among protection systems. The accuracy of Petri net models are improved by phase angle shifts in the voltage waveforms of renewable energy generation resources and the main power supply using Fast Fourier Transform (FFT) through which the Petri net model inputs was corrected.

Keywords: Electrical Power System, Protection Coordination Strategies, Automation, Petri Nets Method.

Petri Ağı Yöntemi Kullanılarak Yenilenebilir Enerji Üretim Kaynaklı Elektriksel Güç Sistemlerinde Koruma ve Röle Koordinasyon Stratejisinin Belirlenmesi

ÖZ

Elektriksel güç sistemindeki koruma prensibi oluşacak olan arızaların zamanında belirlenmesini ve güç şebekesindeki arızalanmış kısımların en uygun zamanda izole edilmesini amaçlar. Bu durum koruma cihazları arasındaki koordinasyon sayesinde gerçekleştirilir. Enerji iletim sistemlerine yenilenebilir enerji üretim kaynaklarının bağlanması güvenlik koordinasyonunun devre dışı kalmasına veya koruma koordinasyon bölgesinin azalmasına sebep olarak sistem korumasını karmaşıklaştırmaktadır. Özellikle bu tarz sorunlar yenilenebilir enerji üretim kaynaklarının etkisindeki güç şebekelerinde daha da şiddetli hale dönüşür. Bu nedenle, geleneksel güç koruma yöntemleri yenilenebilir enerji üretim kaynakları içeren yazılım stratejileri gerektiren bu tür şebekelerde yetersizdir. Bu amaçla bu çalışmada, yenilenebilir enerji üretim kaynaklarının var olduğu güç iletim şebekelerindeki arızalanmış bölümlerin tahmin edilmesi ve koruma koordinasyon şemalarının tasarlanması için Petri ağı metodu kullanılmıştır. Petri ağı yöntemine giriş olarak otomasyon sistemlerinden elde edilen koruma elemanlarının durumu hakkındaki bilgiler kabul edilmiştir. Yenilenebilir enerji kaynaklı üretimlerin etkisi koruma sistemleri arasındaki uyumsuzluğun riskini arttırabilir. Petri ağı modellerinin doğruluğu yenilenebilir enerji üretim kaynaklarına ait gerilim dalga formlarındaki faz açısı değişimleri tarafından geliştirilmiştir ve ana güç kaynağı Petri ağı model girişleri sayesinde Hızlı Fourier Dönüşümü (HFD) kullanılarak düzeltilmiştir.

Anahtar Kelimeler: Elektriksel güç sistemi, Koruma koordinasyon stratejileri, Otomasyon, Petri ağları yöntemi.

NOMENCLATURE

P: Place
T: Transition
M: Marking Vector
R: Relay
CB: Circuit Breaker
BLR: Blocking Under Voltage Protection Relay
MLR: Main Directional Protection Relay
SLR: Substation Local Backup Protection Relay

*Sorumlu Yazar (Corresponding Author)
e-posta: nihatpamuk@gmail.com
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Lx_{Sm}: X[th] Transmission Line Overload Protection Relay

Lx_{Sp}: X[th] Transmission Line Overvoltage Protection Relay

Lx_{Rs}: X[th] Transmission Line Phase Fault Protection Relay

Lx_{Rm}: X[th] Transmission Line Earth Fault Protection Relay

Lx_{Rp}: X[th] Transmission Line Overlap of Protection Relay

Tx_{S}: X[th] Circuit Breaker Failure Protection Relay

PNM: Petri Net Method

FFT: Fast Fourier Transform

PACs: Phase Angle Changes

REGs: Renewable Energy Generation Resources

SCADA: Supervisory Control And Data Acquisition

1. INTRODUCTION

The power transmission systems are the closest sectors to the industrial consumer. Hence, it is a top priority to ensure their protection. Any interruption in the energy exchange and untimely pause in the transmission lines will lead to complete shutdown. The downtime and the damage can be minimized through immediate detection of the defective element or the potential failure in order to be carefully isolated from the rest of the power system [1]. On the other hand, the connection of renewable energy generation to the power systems is increasingly growing due to its technical, economic and environmental advantages [2], [3]. In addition to its multiple advantages, the involvement of the "Renewable Energy Generation Resources" (REGs) in the power transmission network will cause problems such as disordered protection devices, protection blindness, increase and decrease in the level of short circuit current, unwanted power network islanding and re-closer a-synchronization [4], [5].

In recent years, several methods have been proposed for fault detection and estimation of fault section in a power transmission system. In article [6] effort was mainly made to improve a model for performance of protection and detection devices through Petri net models, by which the fault display alarms and security relay alarms and monitoring of automation system are performed. With respect to the effects of REGs engagement, such alarms will be further affected, thus overshadowing the monitoring procedure [4]. At the same time, the proposed Petri net model has a weakness in monitoring.

In references [3], [5] a method was proposed for monitoring the protective system of power transmission networks involving REGs based on Petri nets. Accordingly, the defect of high current protection relay was detected through the Petri net. In these articles, the fault current and the protective device coordination curve were adopted even though it was not clear how the fault current were used in the models. In addition, the accurate detection of faults by the models proposed in these articles, there should be complete information about the occurrence of faults on the transmission line. This is contradictory to the purpose of fault detection performed on the basis of knowledge control center. In this way, it is not clear whether any fault has occurred according to the knowledge control center, or whether the inaccurate knowledge has been received due to unreliable data or protective inconsistency, thus leading to the operator's mistake.

Reference [7] focused on protection of looped power transmission systems based on Petri net involving the REGs. The target of this paper is to provide a supporting protective structure for REGs in the power network, where the Petri net model is used to monitor the proper protection of REGs. This article did not explore how the protective devices coordinated after adding the structure. In fact, a model has been presented on how the protective system functions through the Petri net. Furthermore, little has been discussed about how the knowledge is received from the control center as the suggested model are based on case study not enjoying accuracy and comprehensive effectiveness. None of these studies suggested a perfect model of power system fault detection in the presence of REGs and how to identify the malfunctioning protective devices due to the impact of REGs.

These imply the need for software measures to protect the power transmission network, especially when involving the REGs. Since the power transmission system automation techniques have been widely accepted and the communication substructure has well been improved, the protection scheme based on microprocessors can be employed with communication facilities [8], [9]. For this purpose, the status of protective elements of the transmission system can be achieved by the Energy Control Center, which can in turn be applied for detecting faults in the power transmission networks. The restoration of an electrical power system under the critical fault conditions requires not only great skill and information of the system components, system performance and how the protective relays function, but also accurate and rapid decisions made based on relevant information. Such important and complex tasks can be accomplished by Petri net models. For that purpose, this paper adopted a new tool as Petri net models for the detection of faults in the power transmission network involving the REGs. These models carry out the detection and localization of faults much faster and far more reliably than human operators.

This study was written to present a methodology of multi-criteria selection for relay coordination strategy scheme for power system using Petri Nets Method (PNM). The PNM is a method to derive ratio scales from paired comparisons which obtained from actual criteria's and alternatives and has been identified as a suitable technique for dealing with complex decision making especially during breakdown happened. Renewable energy resource generations effect can increase the risk of disharmony among protection systems. The idea of proposing this methodology to power system came out when the large contingency occurs and had effected to major shutdown to one of the system ring which had happened. The accuracy of Petri net models are improved by phase angle shifts in the voltage waveforms of renewable energy generation resources. The application of "DIgSILENT Power Factory V14" software have been used to analyzed the actual data and it is very reliable software to be amended in future if any data have been updated. The result and discussion also being discussed and well justified using Phase Angle Changes (PACs) and Fourier Transform (FFT) for better understanding on the finding results. As a conclusion, the PNM is a very reliable method to be used for relay coordination strategy scheme and several recommendations were proposed to ensure the reliability of the method will be parallel with the upgraded power system in future.

2. AN INTRODUCTION TO PETRI NETS

The Petri net was first suggested by Adam Petri in 1962 as a tool for modeling computer systems. Petri net is an ideal strategy for graphical modeling based on mathematical logic [10]. Petri nets can be employed for modeling, describing and analyzing systems with concurrent, distributed, parallel or random nature [11], [12]. Petri net is a combination of four elements expressed as C = (P, T, I, O) where P is a set of places, T is a set of transitions, I is the input function and O is the output function. Functions I and O bridge between the transitions (T) and places (P) interconnecting the elements P and T. I is an input function and it's a mapping of transition t_i to the set of places. $I(t_i)$ is known as transition input places. O is an output function and it's a mapping of transition t_i to each of the places. $O(t_i)$ is known as output places. The structure of Petri net is defined by places, transitions, input and output functions. Moreover, set of places (P) and set of transitions (T) are formulated in equation 1.

$$P = \{p_1, p_2, p_3, \ldots\ldots, p_n\}, \quad n \geq 0$$
$$T = \{t_1, t_2, t_3, \ldots\ldots\ldots, t_m\}, \quad m \geq 0 \tag{1}$$

$P \cap T = \Phi$, The set of places and transitions are disjoint.

$I : T \rightarrow P^{\infty}$: The input function is a mapping from transitions to the bags of places which are specified as input places to transitions and P^{∞} shows the bags of places.

$O : T \rightarrow P^{\infty}$: The output function is a mapping from transitions to the bags of places which are specified as output places to transitions.

Place p_i is an input place from transition t_i, where if $p_i \in O(t_i)$ is true then $p_i \in I(t_i)$ is an output place.

As for the Petri net graph, there are two types of nodes defined: Place indicated in the form of a circle and transition indicated in the form of a rectangular (▭) or vertical line (|). Furthermore, a number of directed arcs (arrows) are connected from places to transitions (input places), while the other directed arcs are connected from transitions to places (output places) [13], [14]. Places represent the "status" such as a memory, as the transitions represent an "event" such as faults. Figure 1 displays an example of a Petri net graph.

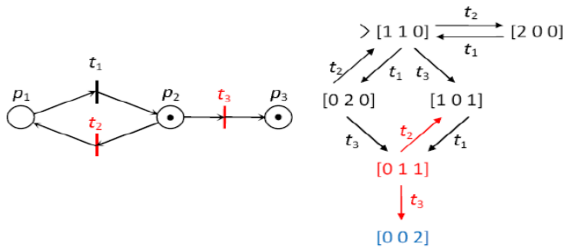

Figure 1: An example Petri net graph

The structure of Petri net and the process of firing transitions can be expressed and analyzed using matrix operations. To do this, the original matrices C, M and U respectively structure, marking and firing vectors are required. The structure matrix is used to represent the topology of Petri nets. The dimensions of this matrix are $|P| X |T|$ defined as equation 2.

$$C(p,t) = \begin{cases} -w(p,t) & \text{if } (p,t) \in F \\ w(p,t) & \text{if } (t,p) \in F \\ 0 & \text{otherwises} \end{cases} \tag{2}$$

Where $|P|$ and $|T|$ are respectively the number of sets P and T, w (p, t) is the weight of arc from P to T, and F is the set of arcs. Moreover, (p, t) € F implies there is a link from p to t. For example, the matrix structure of the Petri nets in figure 1 is represented in equation 3.

$$C = \begin{matrix} & t_1 & t_2 & t_3 \\ p_1 \\ p_2 \\ p_3 \end{matrix} \begin{bmatrix} -1 & 1 & 0 \\ -1 & -1 & -1 \\ 0 & -1 & 1 \end{bmatrix} \tag{3}$$

The marking vector $M_{|P|X|1|}$ illustrates the number of tokens in places. Element 1 or more in this vector illustrate the number of tokens in the corresponding place, while element 0 implies there are no tokens in the corresponding place. The dynamic behavior of Petri nets in figure 1 can be formulated as equation 4, where M_0 is the primary marking vector. References [15, 16] totally described hot to analyze and utilize equations 1 to 4.

$M_1 = M_0 + CU$ (4)

The integer vector C, and incidence matrix U are defined by equation 4. The expression of CU is defined as multiplication of incidence matrix (ratio of tokens) with integer vector. Equation 4 provides a necessary but not sufficient condition; all markings reachable from M_o are solution of equation 4, but not vice versa. A solution to equation 4 exists for any integer vector, but the transition firing sequence represented by integer vector.

3. THE APPLICATION OF PETRI NETS MODEL IN RELAY COORDINATION STUDY

As defined in the IEEE standard, power transmission automation is a system that enables a power transmission company for remote monitoring, coordinating and commanding over the power transmission equipment in real-time and long distances [17]. In general, the remote control and monitoring systems entail one or several control centers as controller stations and a number of terminals as stations under control. Terminals are installed at remote stations, which collect and prepared the information required by the center. This information is recorded and processed at the center which sends the control commands. These commands are received at the terminal and are applied through the mediator equipment to the systems under control [4]. The proposed method is applied to the high-penetration 30-bus power transmission network of REGs [18]. Figure 2 is a single-line view of 30-bus power transmission network. The system information has been given in [19]. It should be noted that, according to [20], the numerical order of relays is based on the number of corresponding power transmission line.

Hence, relay R_i, is for power transmission line number i (L_i) and relay R_{REGsj}, is for renewable energy generation resources $REGs_j$ (i =1,2,3, ..., 30, j=1,2,3, .., 6). For example, relay R_1 is for power transmission line number 1 ($Line_1$), relay R_2 is for power transmission line number 2 ($Line_2$) and relay R_3 is for power transmission line number 3 ($Line_3$). Relays R_{REGs1}, R_{REGs2} and R_{REGs3} are related to the renewable energy generation resources G_1, G_2 and G_3, respectively. In this study, the test system was simulated through "DIgSILENT Power Factory V14" software. At the next stage, the suggested method was implemented by writing the information of voltages as three cycles in each fault through MATLAB software.

The aim of the study is presented for determining the maximum capacity of REGs for maintaining the relay coordination of power transmission system's protection devices. The Petri Net Method (PNM) is able to do all kind of relay coordination owing to time difference flexibility between selectivity zones in simulation. PNM is based on dividing an existing power transmission network into several zones which each of them is capable of operating in islanding mode. Relay coordination with both compulsory instant setting and without instant setting, time-selectivity and instantaneous selectivity are made in relay coordination via DIgSILENT Power Factory V14 software. The standard inverse time-current characteristic form is used based on IEC 255-3 standard in the relay coordination. Instantaneous operating modes are used in single line, two lines and three lines phase-short circuit current. Tripping at the requested time at 10 times of the nominal current of the backup protection is provided in inverse-time study mode. The result and discussion also being discussed and well justified using

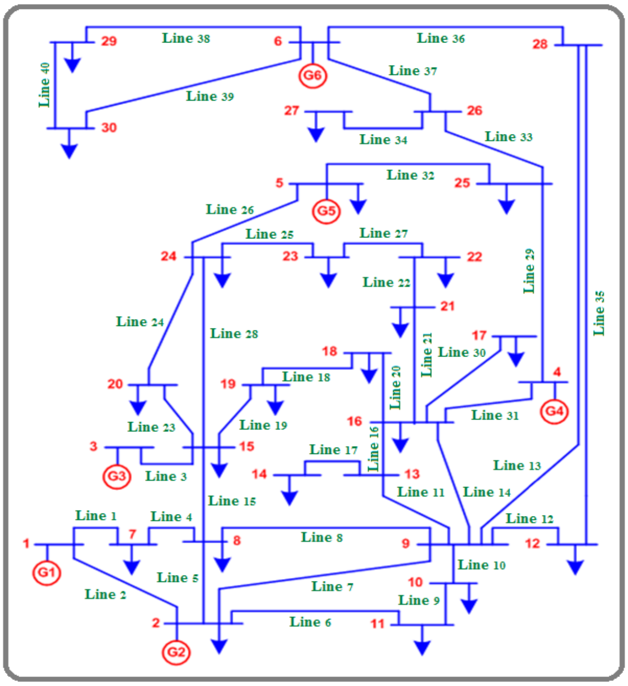

Figure 2: A single line view of 30-bus power transmission network [18].

Phase Angle Changes (PACs) and Fourier Transform (FFT) for better understanding on the finding results. In the suggested approach, the contribution of REGs in fault current is limited through considering mathematical equations of characteristics of protection devices. Consequently, the numerical results are presented in order to confirm the authenticity of suggested approach. The PNM is a very reliable method to be used for relay coordination strategy scheme and several recommendations were proposed to ensure the reliability of the method will be parallel with the upgraded power system in future. The protection principle is shown in Figure 3.

the protection system associated with R_1 are shared by these protection systems, and hence no common modes of failure between R_1 and R_4, R_9 and R_{10} are possible. These remote backup protections will be slower than R_1, R_2 or R_3; and also remove additional elements of the power system namely lines 5, 7 and 6 from service, which would also de-energize any loads connected to these lines. A similar set of backup relays is used for the power system behind bus station 1.

Figure 4 indicates the Petri net model for relay coordination study in power transmission line 2 of the 30-bus power transmission network under study. In this

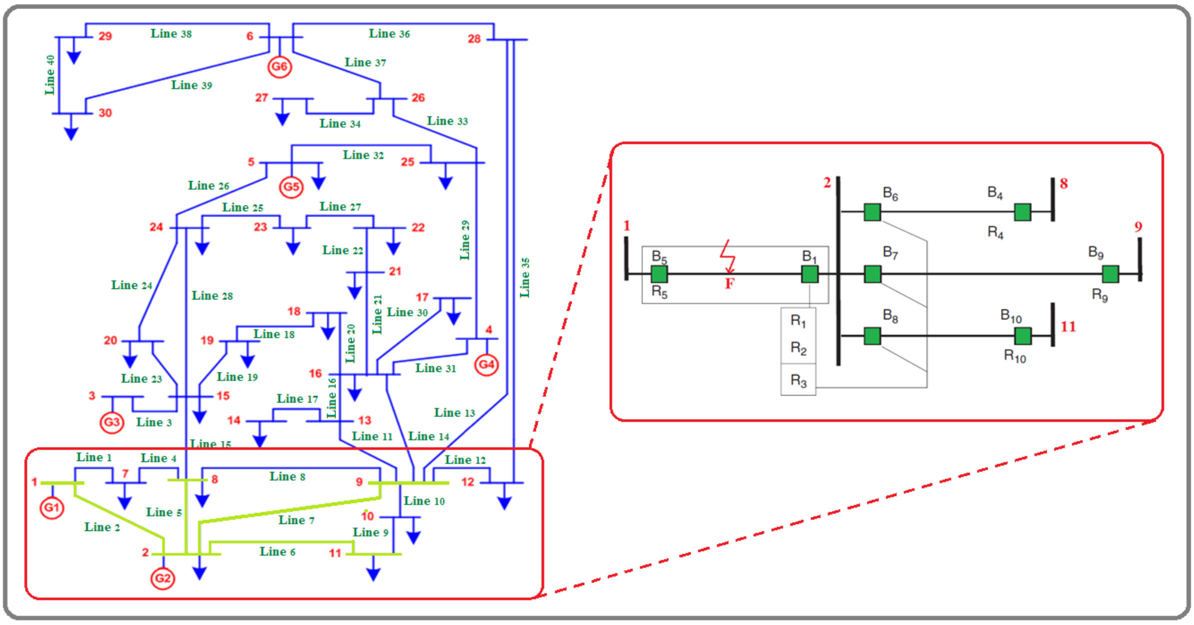

Figure 3: Duplicate primary, local backup and remote backup protection principles for line 2

The fault is assumed at location F. It is inside the zone of protection of transmission line 2. Primary relays R_1 and R_5 will clear this fault by acting through circuit breakers B_1 and B_5. At bus station 2, a duplicate primary relay R_2 may be installed to trip the circuit breaker B_1 to cover the possibility that the relay R_1 may fail to trip. R_2 will operate in the same time as R_1 and may use the same or different elements of the protection chain. For instance, on transmission lines it is usual to provide separate circuit transformers, but use the same potential device with separate windings. The circuit breakers are not duplicated but the battery may be. On lower voltage circuits it is not uncommon to share all of the transducers and direct current (DC) circuits. The local backup relay R_3 is designed to operate at a slower speed than R_1 and R_2; it is probably set to see more of the power system. It will first attempt to trip circuit breaker B_1 and then its circuit breaker failure relay will trip circuit breakers B_5, B_6, B_7 and B_8. This is local backup relaying, often known as circuit breaker failure protection, for circuit breaker B_1. Relays R_9, R_{10} and R_4 constitute the remote backup protection for the primary protection R_1. No elements of

model, the data for protective elements were used as model input. In Figure 4, places CB_{12}, CB_6, CB_{27}, CB_{13}, CB_{14}, CB_{15}, CB_{32}, CB_8, $L2_{Ss}$, $T3_S$ and $T4_S$ represent the corresponding relays in Figure 2, which are the main protection for power transmission line 2 according to [21]. Place $L2_{Rs}$ represents relay transmission line 2 in figure 2, which is the first backup protection for relay $L4_{Rs}$ according to [22]. Similarly, relays CB_7, CB_{11}, CB_4, CB_5, CB_{28}, $T1_S$, $T2_S$, $L1_{Sm}$ and $L1_{Rm}$ are secondary backup protection relays for transmission line 2 where $L3_{Rs}$ is for transmission line 4 while and $T2_S$, $L3_{Rs}$ are for transmission line 4 while and $L1_{Sm}$, $L1_{Rm}$ are for the main source. Moreover, Place $P_{L1(6)}$, $P_{L1(7)}$, $P_{L1(9)}$, $P_{L1(10)}$, $P_{L1(11)}$, $P_{L1(12)}$ represents relay R_1 and R_2 in figure 2 network as the secondary backup protection for relay R_7, R_8, R_9, R_{10} and R_{11}. Similarly, the first, second and third backup protections in the model has been displayed in figure 4 for $P_{L1\,(13)}$ and $P_{L1\,(14)}$. Places $P_{L1\,(3)}$, $P_{L1\,(4)}$, $P_{L1\,(5)}$ and $P_{L1\,(8)}$ have no physical reality applied only as auxiliary places in accordance with the rules of Petri nets. The place of $Line_2$ specifies the fault in transmission line 2.

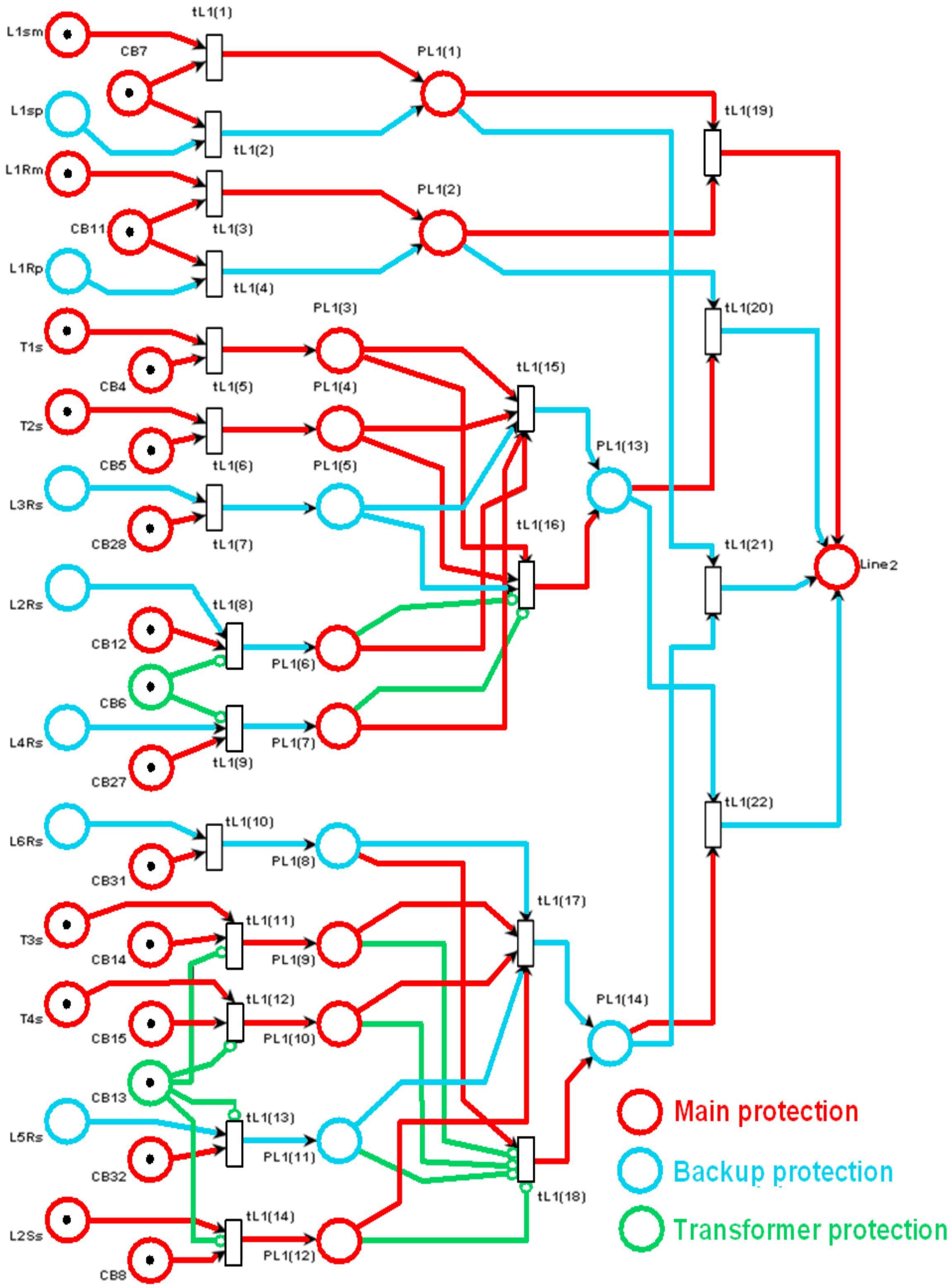

Figure 4: The petri net model for relay coordination study in power transmission line 2 of the 30 bus power transmission network

Furthermore, transitions $t_{L1\,(15)}$, $t_{L1\,(16)}$ and $t_{L1\,(18)}$ have no physical reality applied only for communication between places in accordance with the Petri net rules. In the same way, such a model can be improved for each segment of the power transmission network where the faulted section can be detected through the information on status of protective elements as shown in figures 5 and figure 6.

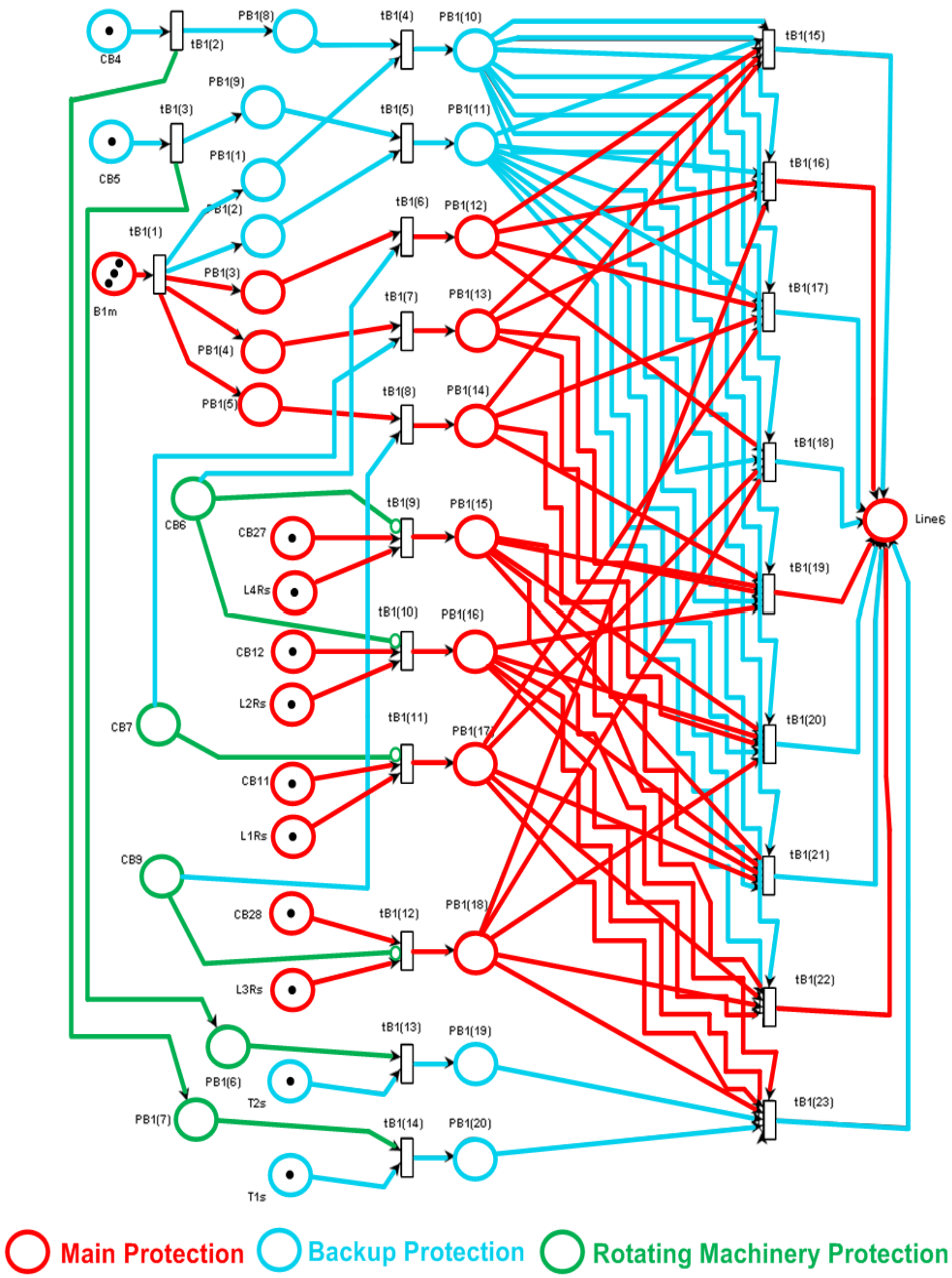

Figure 5: The petri net model for relay coordination study in power transmission line 6 of the 30 bus power transmission network

Since the penetration of REG into the 30-bus power transmission network under study is extremely high, it is likely to face protection disharmony [4], [9] which should be considered in estimating the relay coordination strategy.

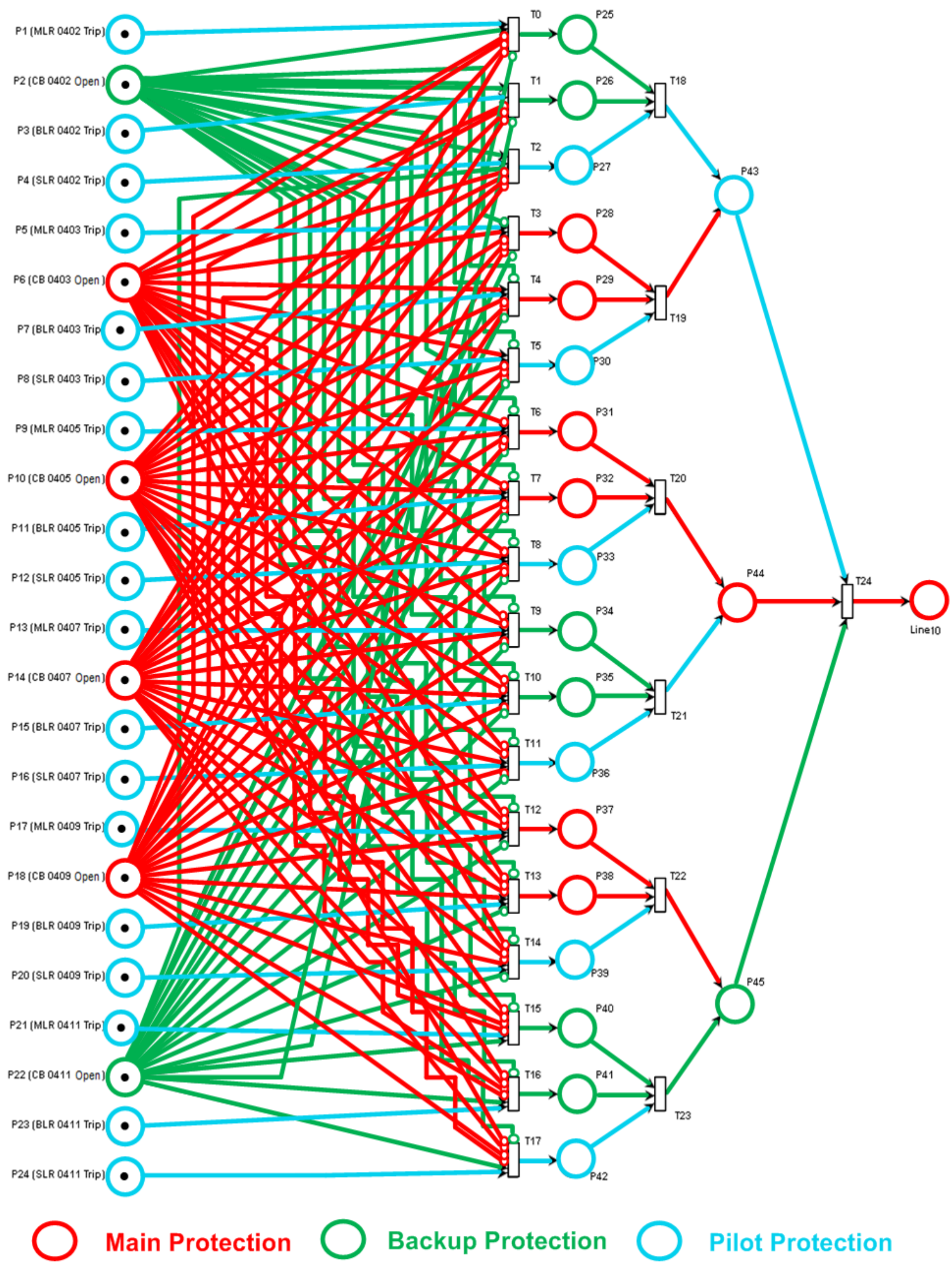

Figure 6: The petri net model for relay coordination study in power transmission line 10 of the 30 bus power transmission network

In these models, the PQ measurements were used at the REG places and power transmission substations in order to measure the voltage of sources. The method presented in [23] was employed to change their angles, which both identified the type of fault and determined whether there was fault between the two sources. As such, the maximum angle change belongs to the two sources between which the fault is detected. In this procedure, the input information to the Petri net model can be corrected through such data, i.e. the status of elements in contradiction with the above detection will be eliminated from the model inputs or incomplete input information will be completed. Here, the Phase Angles Change (PAC) for voltages of REGs and the main source is calculated based on the methodology presented in [24]. In this method, the PQ measurement at the beginning of the bus connection at each of the power supplies was applied to determine the voltage of these resources, thereby to measure the voltage waveform through conversion of Fast Fourier Transform (FFT) into PAC. The voltage of resources will be zero as soon as the PAC fault occurs [25]. In other words, the close the fault to the power supplies the higher the PAC. Therefore, the fault zone between the resources can be specified.

4. NUMERICAL ANALYSIS RESULTS

For the relay coordination applications, the following three scenarios are considered for the power transmission network based on REGs:

- A single line phase fault (phase B to ground) occurred on power transmission line 2.
- Three line phase fault occurred at power transmission line 6.
- Two line phase fault (A-C) occurred on power transmission line 10.

In the first scenario, the fault current is 1630 A. The current passing through relay CB_6, CB_7, CB_8, CB_{12}, CB_{27} and CB_{32} connected to the beginning of power transmission line 2 belonging to the G_1 and G_2 in the fault current feed is 876 A. The share of G_3, G_4, G_5 and G_6 from the fault current feed is 473 A. Since the regulating current of relay CB_7 is 1000 A, it will not respond to the above fault. Furthermore, the status information of $t_{L1\,(1)}$, $t_{L1\,(2)}$, $t_{L1\,(8)}$, $t_{L1\,(9)}$, $t_{L1(13)}$ and $t_{L1\,(14)}$ were received through power transmission automation. According to [26], relay CB_{11} and CB_{31} was specified by index T as the secondary backup protection, relays L_{1Rm} and L_{1Rp} were specified by index S as the secondary backup protections, while relay L_{6Rs} was the main protection. It is assumed that protective coordination has not been fully fulfilled or it was impossible due to high penetration of REGs to fulfill the full coordination. According to the rules of protection configuration, the synchronization petri net model in power system for fault diagnosis is built and shown in figure 7, 8 and 9.

Figure 7 shows the petri net model of block transformer protection of power transmission line 2, which represents the faulty section of that block as CB_{12}, CB_6, CB_{27}, CB_{14}, CB_{15}, CB_{32}, CB_{13} and CB_8. Places $T3_S$, $T4_S$ and $L2_{S5}$ are dedicated to a protective relays group for transformer protection as described previously. Places $L1_{Sm}$, CB_7, $L1_{Rm}$, CB_{11}, $T1_S$, CB_4, $T2_S$, CB_5 and CB_{28} are the corresponding circuit breakers for the section of the block transformer protection unit. Places $L1_{Sp}$, $L1_{Rp}$, $L3_{Rs}$, $L2_{Rs}$, $L4_{Rs}$, $L6_{Rs}$ and $L5_{Rs}$, are virtual nodes and have no physical meaning. This meaning the transformer protection unit or other section is faulty when a one of its own protective relays and other sections protective relays operates with the corresponding circuit breakers together.

Figure 8 shows the petri net model of block rotating machinery protection of power transmission line 6, which represents the faulty section of that block as $B1_m$, CB_{27}, $L4_{Rs}$, CB_{12}, $L2_{Rs}$, CB_{11}, $L1_{Rs}$, CB_{28} and $L3_{Rs}$. Places CB_6, CB_7 and CB_9 are dedicated to a protective relays group for rotating machinery protection as described previously. Places CB_4, CB_5, $T1_S$ and $T2_S$ are the corresponding circuit breakers for the section of the block rotating machinery protection unit. Places $P_{B1(6)}$ and $P_{B1(7)}$ are virtual nodes and have no physical meaning. This meaning the rotating machinery protection unit or other section is faulty when a one of its own protective relays and other sections protective relays operates with the corresponding circuit breakers together.

Figure 9 shows the petri net model of block pilot protection of power transmission line 10, which represents the faulty section of that block as $P_2(CB_{0402})$, $P_6(CB_{0403})$, $P_{10}(CB_{0405})$, $P_{14}(CB_{0407})$, $P_{18}(CB_{0409})$ and $P_{22}(CB_{0411})$. Places $P_1(MLR_{0402})$, $P_5(MLR_{0403})$, $P_9(MLR_{0405})$, $P_{13}(MLR_{0407})$, $P_{17}(MLR_{0409})$ and $P_{21}(MLR_{0411})$ are dedicated to a protective relays group for pilot protection as described previously. Places $P_3(BLR_{0402})$, $P_7(BLR_{0403})$, $P_{11}(BLR_{0405})$, $P_{15}(BLR_{0407})$, $P_{19}(BLR_{0409})$, $P_{23}(BLR_{0411})$, $P_4(SLR_{0402})$, $P_8(SLR_{0403})$, $P_{12}(SLR_{0405})$, $P_{16}(SLR_{0407})$, $P_{20}(SLR_{0409})$ and $P_{24}(SLR_{0411})$ are the corresponding circuit breakers for the section of the block pilot protection unit. Places P_{27}, P_{30}, P_{33}, P_{36}, P_{39} and P_{42} are virtual nodes and have no physical meaning. This meaning the pilot protection unit or other section is faulty when a one of its own protective relays and other sections protective relays operates with the corresponding circuit breakers together.

The initial token distribution is confirmed according to the received information from SCADA system in the control room. After finishing initial token distribution, the transition matching the condition will be fired. The token will be redistributed in the petri net graph after a series firing of transition until no transition can be fired, and then, the petri net graph reaches the stable status. The fault section can be directly obtained from the petri net graph at that time. The criterion rule is as follows; if there are tokens in place, then that node is the faulted section. Table 1 shows Phase Angle Changes (PACs) for three scenarios in power transmission network.

Table 1: Phase Angle Changes (PACs) for three scenarios in power transmission network

Scenario Number	PACs (rad) A phase	PACs (rad) B phase	PACs (rad) C phase
I	-0.00038	-0.06518	-0.00464
	0.00416	**-0.07123**	0.00413
	0.00169	-0.06214	-0.00846
	0.00137	**-0.06721**	-0.00433
	-0.00083	-0.04162	-0.00564
	0.00046	-0.05211	-0.00287
II	-0.15541	-0.12414	-0.11562
	-0.18580	**-0.13489**	**-0.13145**
	-0.15412	-0.11735	-0.11132
	-0.15434	-0.11877	-0.10754
	-0.19431	**-0.13468**	**-0.12943**
	-0.16417	-0.10792	-0.10982
III	-0.09123	-0.00456	0.03463
	-0.10165	-0.00212	0.03942
	-0.18541	-0.00163	**0.10574**
	-0.10463	-0.00084	-0.00017
	-0.09856	-0.00147	0.03719
	-0.17832	-0.00213	**0.11434**

According to table 1, the fault zone will fall between the source G_1 and G_2. Therefore, it can be concluded that one of the relays among CB_8, CB_{12}, CB_{14}, CB_{15}, CB_{27} and CB_{32} should have been activated with $t_{L1\ (8)}$, $t_{L1\ (9)}$, $t_{L1\ (11)}$, $t_{L1\ (12)}$, $t_{L1\ (13)}$, $t_{L1\ (14)}$ which failed. Now, applying the information received from the power transmission automation and the results of table 2 to the Petri net models of transmission line 2 will have output. It should be noted that the data in table 1 from figure 7 Petri net models, a token has been assumed in relay CB_7 specified as a star. Figure 7 displays the marking of Petri model in Figure 4 based on the relay status information received from power transmission automation system and information in table 1.

In the Figure 7 model, transitions $t_{L1\ (8)}$, $t_{L1\ (9)}$, $t_{L1\ (11)}$, $t_{L1\ (12)}$, $t_{L1\ (13)}$, $t_{L1\ (14)}$, $t_{L1\ (15)}$, $t_{L1\ (16)}$, and $t_{L1\ (18)}$ will be fired on the basis of the Petri net rules as places $p_{L1\ (6)}$, $p_{L1\ (7)}$, $p_{L1\ (9)}$, $p_{L1\ (10)}$, $p_{L1\ (11)}$, $p_{L1\ (12)}$, $p_{L1\ (13)}$ and $p_{L1\ (14)}$ will entail tokens. Then, transition $t_{L1\ (19)}$ will fire marking the place of $Line_2$, Hence determining whether there is fault in power transmission line 2. Figure 8 shows the marking of Petri model in figure 5 based on the relay status information received from power transmission automation system and information in table 1. Figure 9

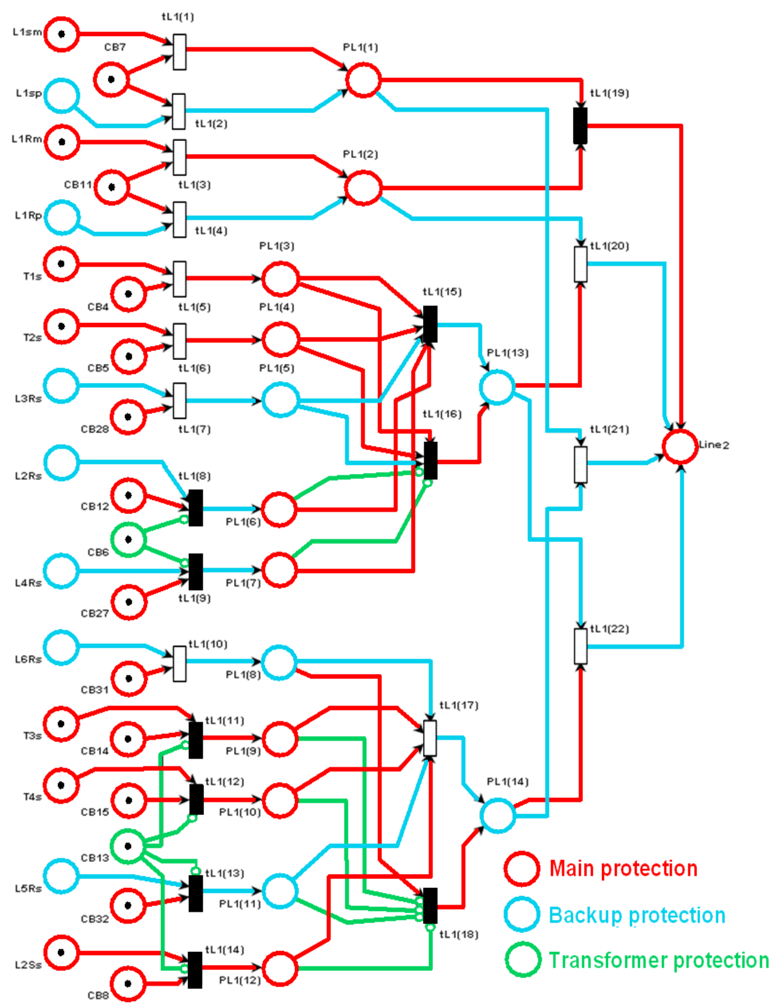

Figure 7: Marking of figure 4 petri net model for scenario I.

shows the marking of Petri model in figure 6 based on the relay status information received from power transmission automation system and information in table 1.

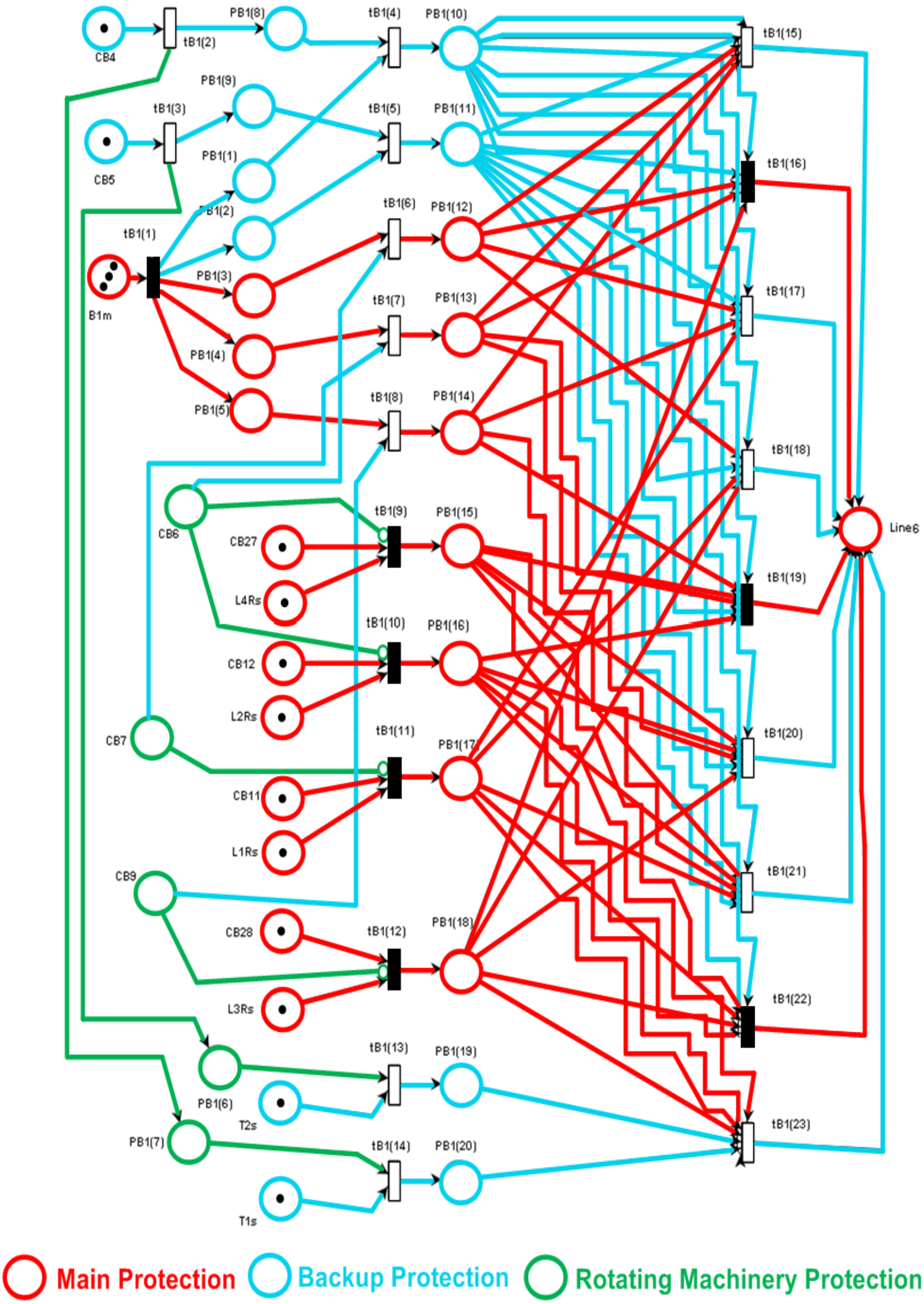

Figure 8: Marking of figure 5 petri net model for scenario II.

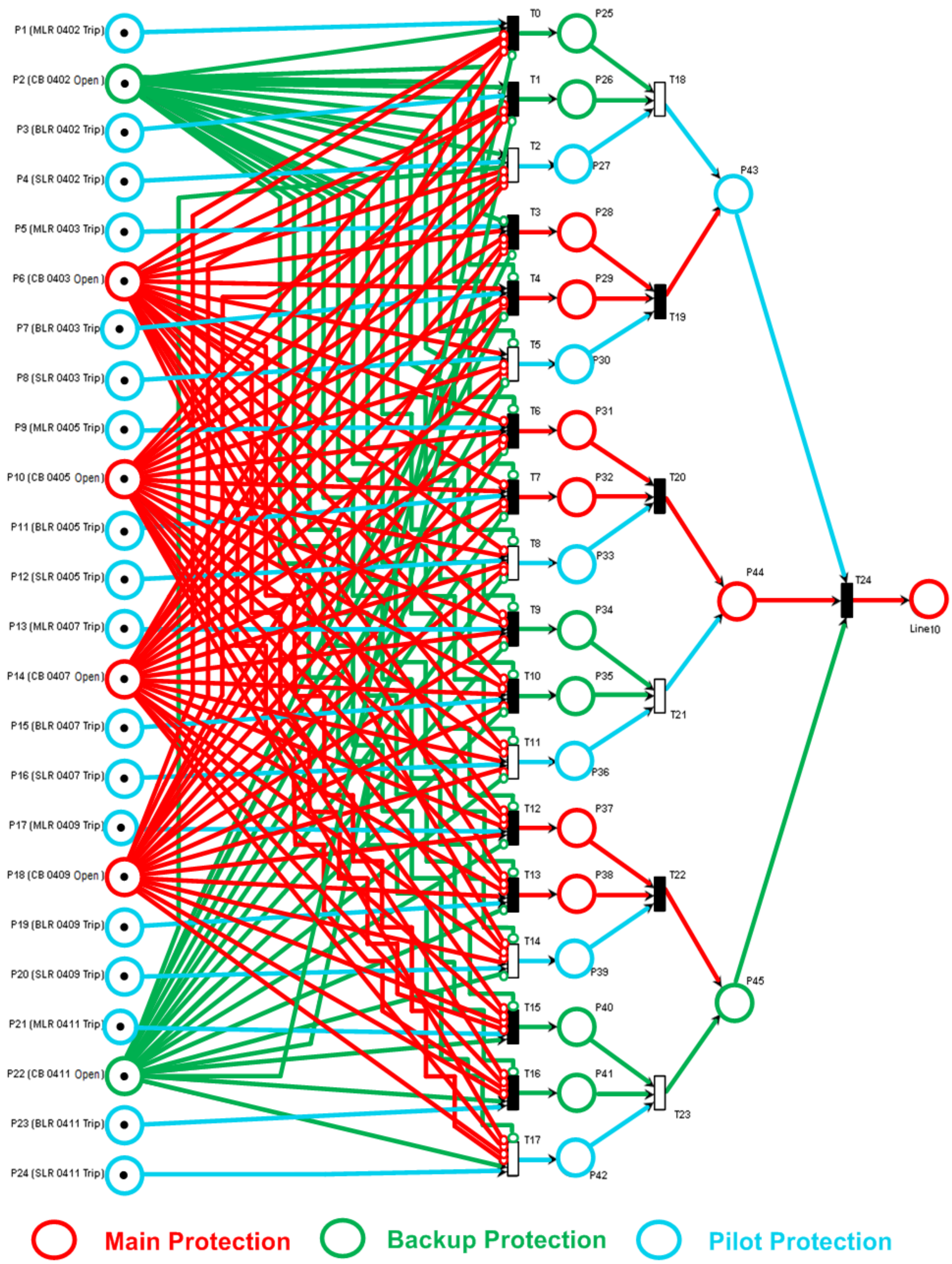

Figure 9: Marking of figure 6 petri net model for scenario III.

. In the second scenario, the fault current is 5393 A. The current passing through relay B_{1m} is 4885 A, of which 3012 A belongs to the network share, while the current passing through relays CB_{11}, CB_{12}, CB_{27}, CB_{28}, L_{1Rs}, L_{2Rs}, L_{3Rs} and L_{4Rs} are 1078 A which is more than the regulated current and CB_{28}, L_{3Rs} will respond to the fault. Furthermore, the status information of $p_{B1\,(15)}$, $p_{B1\,(16)}$ and $p_{B1\,(18)}$ were received through power transmission automation. According to table 1, the faulted zone will fall between the Bus_{11} and G_6. Now, applying the information received from the power transmission automation and the results of table 1 to the Petri net models of lines Bus_{11} and G_6, only the Petri net model of transmission line 6 will have output. It should be noted that the type of fault are specified by criteria |PAC|>0.05 and data from table 1. In the third scenario, the fault current is 3155 A, to which relays P_2, P_6, P_{10}, P_{14}, P_{18} and P_{22} respond and the status information is received through the power transmission automation. According to table 1, the faulted zone will fall between the Bus $_9$ and Bus $_{10}$. Table 2 reports the operating of the protection relays, tripping circuit breakers and diagnosis of faulted sections in power transmission network for all scenarios.

operation of bus station bus differential relays P_{37} and P_{38}. Following the operated relay many circuit breakers are tripped these circuit breakers are the first circuit breaker for block 1 (P_{17} and P_{18}), block 2 (P_{21} and P_{22}), block 3 (P_{13} and P_{14}), block 4 (P_9 and P_{10}), block 5 (P_5 and P_6) and transmission line 10 (P_1 and P_2). The pilot protection of power transformer is operated and tripped the following circuit breakers; the first and second circuit breakers of block 1 and block 2. Applying petri net on fault diagnosis based on the final status of circuit breakers and the protective relays are easily used to determine the faulty sections in that scenario as well as a simple fault.

Table 2: Operating of the protection relays, tripping circuit breakers and diagnosis of faulted sections for three scenarios in power transmission network

Scenario	Operated Relay	Tripped CBs	Petri Net Diagnosis
I	$P_{L1(1)}$, $P_{L1(3)}$, $P_{L1(4)}$, $P_{L1(8)}$	CB_6, CB_8, CB_{12}, CB_{13}, CB_{14}, CB_{15}, CB_{27}, CB_{32}	The faulted section is transmission line 2
II	$P_{B1(1)}$, $P_{B1(2)}$, $P_{B1(3)}$, $P_{B1(4)}$, $P_{B1(5)}$, $P_{B1(15)}$, $P_{B1(16)}$, $P_{B1(17)}$, $P_{B1(18)}$	$B1_m$, CB_{27}, $L4_{Rs}$, CB_{12}, $L2_{Rs}$, CB_{11}, $L1_{Rs}$, CB_{28}, $L3_{Rs}$	The faulted section is transmission line 6
III	P_{25}, P_{26}, P_{28}, P_{29}, P_{31}, P_{32}, P_{34}, P_{35}, P_{37}, P_{38}, P_{40}, P_{41}	P_1, P_2, P_5, P_6, P_9, P_{10}, P_{13}, P_{14}, P_{17}, P_{18}, P_{21}, P_{22}	The faulted section is transmission line 10

For scenario 1: Petri net fault diagnosis method directly determines the faulted section with transmission line 2 based on its own operated relay $P_{L1(1)}$, $P_{L1(3)}$, $P_{L1(4)}$ and $P_{L1(8)}$ which leads to trip the corresponding circuit breakers of that faulted transmission line 2 as; generation units' circuit breakers and the double-circuit breakers of the block transformer protection unit. (The first and second circuit breaker) The proposed method determines the faulted transformer although there are a lot of alarms and tripping signals received in the power station control room.

For scenario 2: A lot of alarms and tripping signals are received in the power generation station control room. These signals include the tripping signals such as operated protective relay $P_{B1(1)}$, $P_{B1(2)}$, $P_{B1(3)}$, $P_{B1(4)}$, $P_{B1(5)}$, $P_{B1(15)}$, $P_{B1(16)}$, $P_{B1(17)}$ and $P_{B1(18)}$, alarm signals such as tripping the related circuit breakers as; $B1_m$, CB_{27}, $L4_{Rs}$, CB_{12}, $L2_{Rs}$, CB_{11}, $L1_{Rs}$, CB_{28} and $L3_{Rs}$, and finally, a large number of events appear resulting of that fault. The operator needs to process these signals, although that information is so large that human ability to comprehend can easily be overwhelmed. Petri net solves this situation shortly and computes the faulted section with transmission line 6.

For scenario 3: This scenario is considered as a simulation of a multiple fault may be occurred in the power transmission line 10 and makes confusion to the operators due to a lot of information (events, tripping signals, alarm signals) need to be processed. This fault may cause the power transmission line 10to outage which in turn leading to whole the power system to the breakdown. The fault occurred in bus station 9 by

5. CONCLUSIONS

The presented method allows dealing with power transmission network with high penetration of REGS that introduces problems such as losing coordination of protection devices with consequence false tripping. The presence of REGs in the power transmission network, especially under the extreme penetration of these resources, will most likely lead to protective disharmony or there will not be any possibility to perfectly maintain protective coordination. This important factor can inhibit the application of REG generations due to their economic and environmental advantages. In this paper, protection and relay coordination strategy was proposed through the Petri net models for determining the faulted section of the power transmission network in presence of REG. In this method, the Petri net models were adopted for fast processing of information received from power transmission automation. The effectiveness of the method has been demonstrated by means of critical scenarios study related to protection systems and REGs.

In these scenarios study, in presence of a three phase fault, the loss of coordination in protection system is detected and the correct location of fault is obtained. In solving the problem of uncertainty facing to the information received from power transmission automation due to presence of REGs, it is recommended that active and reactive power measurements be employed at REGs and power transmission substations in order to determine the voltage of these generator resources and change their angles for detecting the type of fault and also whether there is any error occurred between the two generator resources. By results it's clear that the proposed method can remove a lot of complexity in data analysis and allow managing little information while avoiding cascading failure in power protection system. In this procedure, the maximum voltage angle change between two generator resources will determine whether there is any fault, thus providing an opportunity to modify the input information to the Petri net model. Accordingly, the status of protection elements in contravention with the above detection can be eliminated from the model inputs or the incomplete received information can be completed.

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