Ndjependa *et al.*
Journal of Electrical Systems and Information Technology (2021) 8:17
https://doi.org/10.1186/s43067-021-00039-6

Journal of Electrical Systems and Information Technology

RESEARCH Open Access

A novel approach of a dynamic multi objective optimization of a power distribution system

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Abstract

A new dynamic multi objective optimization approach is covered in this paper. The technique for optimizing the power distribution system is dynamic reconfiguration. The goal is to propose an optimal dynamic reconfiguration which minimizes the active power losses and the voltage deviation of the nodes of the power distribution system according to the energy available at the source, while constantly guaranteeing the supply of the electrical energy to priority consumers. The reliability indices considered in this paper are the system average interruption frequency index (SAIFI) and the system average interruption duration index (SAIDI) and are used to check the reliability of the optimal configurations obtained. This study subdivides a day into periods. The variations in the available power of the source and the power requested by the load, cause a new optimal configuration of the network at each period. In this work, the load adapts to the source and the optimal network topology evolves according to the maximum available power of the source. A mathematical formulation of the dynamic optimization problem by period or piece is proposed. The dynamic approach consists in acquiring the power of the load and of the source by period or piece and to compare them. When the available energy is sufficient, an optimal configuration that minimizes the power losses and voltage deviation while ensuring the supply of electrical energy to all consumers in the network is proposed. On the other hand, when the available energy is insufficient, an optimal topology of the power system minimizing the power losses and voltage deviation while guaranteeing the supply of electrical energy to priority consumers of the network is proposed. The optimal solutions per period are obtained using the MIP and MINLP methods. The approach is implemented on standard IEEE 15, 33 and 69 node power distribution system. The results obtained are satisfactory and prove the effectiveness of this new vision for the conduct of the power distribution system.

Keywords: Dynamic multi objective optimization, Dynamic reconfiguration, Optimal configuration, Available power, Requested power

Introduction

The supervisor of the power distribution system must always make a decision when faced with certain situations. The availability of electrical power and the variation of the power of the load poses the problems for consumer satisfaction. Sometimes, the network supervisor may turn off consumers in case of shortage of power supply. It is imperative to think of an optimal management of the network by a dynamic reconfiguration that proposes an optimal topology which can satisfy the consumers at each period of the day.

Liu and Wang [1] propose a dynamic reconfiguration of a power distribution network by considering the dynamic segmentation of the load profile. The objective function is the minimization of the cost of active power losses, the cost of switching operations during dynamic reconfiguration as well as the network reliability index. The genetic algorithm is used to solve the problem of dynamic reconfiguration. In their work, they do not take into account the improvement in the voltage profile at the node level with each optimal configuration of the network by period. This method is implemented on a standard IEEE 33 bus network. Geng et al. [2] propose a dynamic reconfiguration of an electrical energy distribution network using the PSO (Particle Swarm Optimization) algorithm. The objective is to minimize the active power losses and the number of switching operations. They did not take into account the improvement in the voltage profile at the network nodes. Jafari et al. [3] present a combination of EMA-WGA (Exchange Market Algorithm- Wild Goats Algorithm) to solve the problem of dynamic reconfiguration of a power distribution network. The objective is to minimize the active power losses and the reliability indices of the network by period. They implement this algorithm on IEEE 15, 33 bus test networks. For the 15 bus network. They subdivide the day into 24 periods of equal width (1 h) and the 33 bus network into 8 periods of equal duration. Booth et al. [4] propose an algorithm making it possible to determine all the switching plans of the switches which restore electrical energy in the event of a fault while isolating the section of the network which is faulty. Dantas et al. [5] propose an algorithm based on the stochastic MILP which allows a dynamic reconfiguration of the network in the presence of renewable energy sources. This method always allows consumers to be satisfied at all times. The proposed mathematical model does not contain weighting coefficients, which is not normal since they used the weighting formulation. Jiang and Zhang [6] present a technique which determines a predictive power of the load. Unlike the traditional method of measuring the power demanded by the load, the algorithm uses the predictive value by period or time interval and proposes an optimal configuration of the power distribution system. Wen et al. [7] propose a method that combines topology analysis and real-time reconfiguration of the power distribution network. The change in the parameters of the initial topology causes a dynamic analysis of the topology to ensure the continuity of service of the network and to isolate the faulty areas. The initial configuration in real time is obtained by updating the network parameters. The optimal configuration is one that minimizes power losses and improves the voltage profile at node level in real time. This method is implemented in the absence and presence of faults in the power distribution system. Xu et al. [8] propose an algorithm which minimizes the cost of the distribution of the electrical energy in a system through dynamic reconfiguration. The algorithm used here is the Quantum Particle Swarm Optimization (QPSO). The goal is to minimize the costs of wasted energy and switching operations. For each scenario, an optimal configuration is proposed. This method takes into account other energy sources and is implemented on a 33 bus network. The mathematical model does not contain weighting coefficients which is not normal because it is the formulation by weighting which is used. HuPing et al. [9] propose the static method to solve the problem of dynamic reconfiguration. The objective reconfiguration function is used by optimization interval. The decomposition of time in reduced intervals allows for multiple optimizations. This method is implemented on a 33 bus network. The mathematical model takes into account the start and end time of each period as well as the reconfiguration time. Kovacki et al. [10] propose a method based on Lagrange Relaxation to determine the optimal configurations of the distribution network at each time interval. The objective is to minimize the active power losses under the following constraints: radial configuration, avoid line overloads, avoid voltage drops, limit the number of switching operations. Their work does not improve the tension profile. Novoselink et al. [11] propose a nonlinear predictive control model for the dynamic reconfiguration of a power distribution system. The goal is to propose a control strategy which finds the optimal topology of the network and the optimal backup power to be supplied by the decentralized generators and the energy storage units. Li et al. [12] propose a dynamic reconfiguration in the presence of photovoltaic and wind generators to improve the stability of the network. The reconfiguration here makes it possible to minimize the power losses and the number of switching operations of the switches. The ant colony algorithm is used on an IEEE 33 bus network to find the optimal configuration. Meng et al. [13] propose a dynamic reconfiguration of the power distribution system in the presence of photovoltaic and wind generators based on ant colony algorithms and genetics. The aim is to minimize the costs of energy and switching operations of the switches. The Markov model is adopted to predict the value of the active power of photovoltaic and wind generators every hour. Mosbah et al. [14] propose a dynamic reconfiguration of the power distribution network which considers the variations of the load. The MST (Minimum Spanning Tree) based on the Kruskal algorithm is proposed to determine the optimal configuration of the power distribution system per period. The objective is to minimize active power losses. This algorithm is tested on the IEEE 33 and 84 bus networks and is validated on a real network of 116 buses of the Algerian power distribution network. All these authors have not studied the situation where the available energy is insufficient and does not minimize the voltage deviation at the nodes.

In this paper, we propose a new approach to the study of dynamic reconfiguration. The principle is to adapt the load to the source. The approach is based on two scenarios. The first concerns the periods during which the available power of the source is sufficient. The second scenario concerns the periods during which the available power of the source is insufficient. For each scenario, the algorithm proposes an optimal system topology which minimizes active power losses and voltage deviation and which satisfies consumers. The test of the reliability of the optimal topologies obtained is given by the system average interruption frequency index (SAIFI) and the system average duration index (SAIDI). The method used to check the reliability of the optimal configurations found is borrowed from [3]. However, priority customers must always be supplied with electrical energy. This approach makes it possible to reduce the load when the available power is insufficient, to avoid putting all the consumers of the network off. But when the available power is sufficient, all customers are supplied with electrical energy. In this work, the associated constraints are: limited available energy source, limited number of switching operations, avoid voltage drops at the nodes, the power transit must be radial, avoid line overloads, the maximum possible of consumers must be connected. Unless there is insufficient energy where optimization must take into account technical feasibility, priority consumers must always be supplied regardless of the scenario.

Methods

Problem formulation

Consider the RLC model of a branch of the network given in Fig. 1.

The state model of the circuit is given in Eq. (1).

$$\begin{pmatrix} \frac{\mathrm{d}i(t)}{\mathrm{d}t} \\ \frac{\mathrm{d}v_1(t)}{\mathrm{d}t} \\ \frac{\mathrm{d}v_2(t)}{\mathrm{d}t} \\ \frac{\mathrm{d}i_e(t)}{\mathrm{d}t} \\ \frac{\mathrm{d}i_d(t)}{\mathrm{d}t} \end{pmatrix} = \begin{pmatrix} -\frac{R_1}{L_1} & \frac{1}{L_1} & -\frac{1}{L_1} & 0 & 0 \\ -\frac{1}{C_1} & 0 & 0 & 0 & 0 \\ \frac{1}{C_2} & 0 & 0 & -\frac{1}{C_2} & -\frac{1}{C_2} \\ 0 & 0 & \frac{1}{L_{L2}} & -\frac{R_{L2}}{L_{L2}} & 0 \\ 0 & 0 & \frac{1}{L_{L2}} & 0 & -\frac{R_{L2}}{L_{L2}} \end{pmatrix} \begin{pmatrix} i(t) \\ v_1(t) \\ v_2(t) \\ i_e(t) \\ i_d(t) \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{1}{C_1} \\ 0 \\ 0 \\ 0 \end{pmatrix} i_1(t)$$
$$Y = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} i(t) \\ v_1(t) \\ v_2(t) \\ i_e(t) \\ i_d(t) \end{pmatrix} \tag{1}$$

Y: Output vector

We suppose that $C_1 = C_2 = 0$

$$P_2 = P_1 - P_{P1} - P_{L2} \tag{2}$$

$$Q_2 = Q_1 - Q_{P1} - Q_{L2} \tag{3}$$

P_1: Active power at node 1, P_2: Active power at node 2, P_{P1}: Active power losses in the branch 1–2, Q_1: Reactive power at node 1, Q_2: Reactive power at node 2, Q_{P1}: Reactive power losses in the branch 1–2.

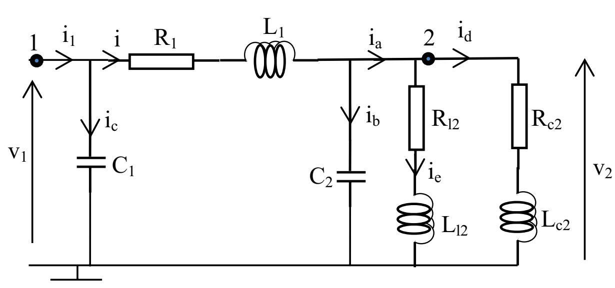


Fig. 1 Branch model RLC with the load and connected of the continuation of the network. R_1: resistance of the branch 1–2, L_1: inductance of the branch 1–2, C_1: capacitor at node 1, C_2: capacitor at node 2, R_{l2}: resistance of the load at node 2, L_{l2}: inductance of the load at node 2, R_{c2}: resistance of the continuation of the network at node 2, L_{c2}: inductance of the continuation of the network at node 2, i_1: total current in the branch 1–2 , i: current in the branch 1–2 , i_c: current in the capacitor C_1 , i_b: current in the capacitor C_2, i_e: current called by the load at node 2, i_a: total current called by the load and the continuation of the network, i_d: current called by the continuation of the network

With:

$$P_{P1} = R_1 I_1^2 \tag{4}$$

$$Q_{P1} = X_1 I_1^2 \tag{5}$$

I_1: RMS value of the total current in the branch 1–2, X_1: reactance of the branch 1–2.

Equations (6) and (7) present the expressions of the total active and reactive power losses of the network.

$$P_{\text{loss}} = \sum_{i=1}^{N_{\text{br}}} \frac{P_i^2 + Q_i^2}{V_i^2} R_i \tag{6}$$

$$Q_{\text{loss}} = \sum_{i=1}^{N_{\text{br}}} \frac{P_i^2 + Q_i^2}{V_i^2} X_i \tag{7}$$

P_i: Active power at node i, Q_i: reactive power at node i, $P_{i+1:}$ Active power at node i + 1, $Q_{i+1:}$ Reactive power at node i + 1, R_i: Resistance of the branch i, X_i: Reactance of the branch i, V_i: RMS value of the voltage at node i, N_{br}: Number of node of system.

An electrical network is a hybrid system therefore comprising continuous and discrete variables. It is continuous by period.

In this work the control variables are the decision variables and represent the state of the switches. These decision variables are binary (closed / open).

We can therefore adopt a strategy which consists of formulating the mathematical problem of dynamic optimization by period and using the MIP (Mixed Integer Programming) methods for the linear model and MINLP (Mixed Integer Nonlinear Programming) for the nonlinear model in order to find the optimal solution per period.

The optimal control function here is the set of state vectors of the optimal switches. An optimal state vector of the switches gives an optimal configuration of the network per period which minimizes the power losses and the voltage deviation as a function of the energy available while guaranteeing the supply of energy to consumers and especially to priority customers whatever the scenario.

The objective function which minimizes the active and reactive power losses per period is given in Eq. (8).

$$\min F = \sum_{m=1}^{N_P} \alpha_m \sum_{i=1}^{N_{br}} \frac{(P_i^m)^2 + (Q_i^m)^2}{(V_i^m)^2} R_i + \sum_{m=1}^{N_P} \beta_m \sum_{i=1}^{N_{br}} \frac{(P_i^m)^2 + (Q_i^m)^2}{(V_i^m)^2} X_i \tag{8}$$

N_p: number of period of the day. α_m, β_m: weighting coefficients. P_i^m: Active power at node i at period m. Q_i^m: Reactive power at node i at period m. V_i^m: RMS value of the voltage at node i at period m.

Constraints

During the reconfiguration, it is necessary to avoid voltage drops at the nodes.

$$V_{i\,\min} \le V_i^m \le V_{i\,\max};\ i = 1, 2, 3, ..., N_{\text{bus}} \tag{9}$$

Avoid overloading the power lines.

$$0 \le I_i^m \le I_{i\,\max};\ i = 1, 2, 3, ..., N_{br} \tag{10}$$

The number of switching operations must also be limited.

$$N_s \le N_{s\,\max} \tag{11}$$

With: $V_{i,\,\min}$: Minimum value of the acceptable voltage at a node, $V_{i,\max}$: Maximum value of the acceptable voltage at a node, I_i: Intensity of line current flowing through a branch, $I_{i,\max}$: Intensity of the maximum line current defined by the manufacturer, N_{br}: Number of branch, N_{bus}: Number of node, N_s: Switching operations number, $N_{s\max}$: Maximum switching operations number.

Ultimately, the constraints are Eqs. (9), (10) and (11).

Reliability assessment

Equations (12) and (13) give the expressions of the SAIFI and the SAIDI.

$$\text{SAIFI} = \frac{\sum N_k}{N_c} \tag{12}$$

$$\text{SAIDI} = \frac{\sum N_k}{N_c} t_c \tag{13}$$

With: N_k: customer impacted by an interruption, N_c: total number of customer, t_c: duration of the interruption.

Problem solving algorithm

In this work, the proposed method is given in Fig. 2.

Description of the algorithm

Step1: Initialization

In this step, we define the number of switches in the system.

Step 2: Initial configuration of the system

We define the initial network configuration.

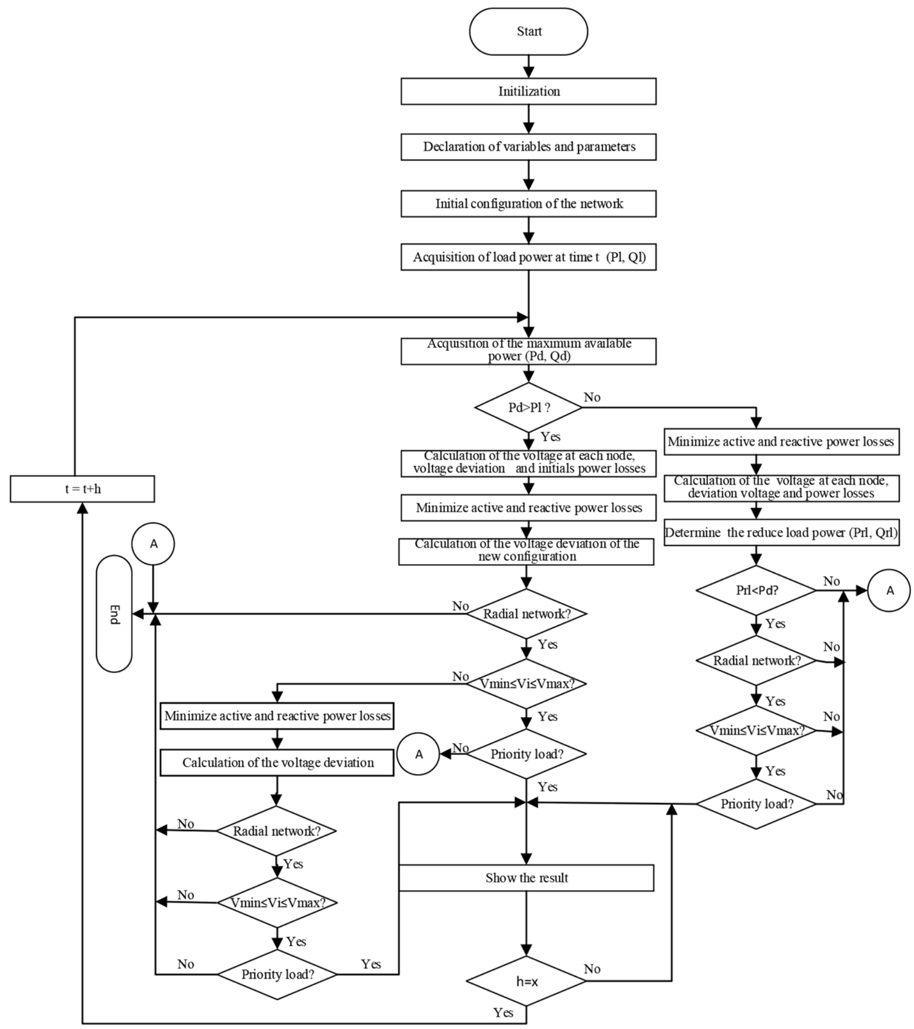
Step 3: Declaration of the variables and parameters

We define the binary decision variables, the optimization variables and the system characteristics.

Step 4: Load power acquisition and available power threshold

Acquire the active (Pl) and reactive (Ql) powers of the load as well as the threshold of the active (Pd) and reactive (Qd) powers available from the source at period m.

Step 5: Minimization of the active and reactive power losses



x : Duration of a period
h : Variable linked of the period

Fig. 2 Problem resolution flow chart

If the available power is sufficient, we calculate the power losses and the voltage on the level of the nodes in the initial structure of the system. We propose an optimal configuration which minimizes the active power losses and the voltage deviation using the MIP solver (Mixed Integer Programming).

Step 6: Load reduction if voltage is unacceptable

If the voltage at the network nodes is out of tolerance, the load must be reduced to provide normal voltage to consumers while always minimizing active power losses and voltage deviation using the MIP (Mixed Integer Programming) solver while now priority consumers supplied with electrical energy.

Step 7: Load reduction if the available power is insufficient

If the available power is insufficient, the load must be reduced to avoid the interruption of the distribution of the electrical energy to consumers by always minimizing

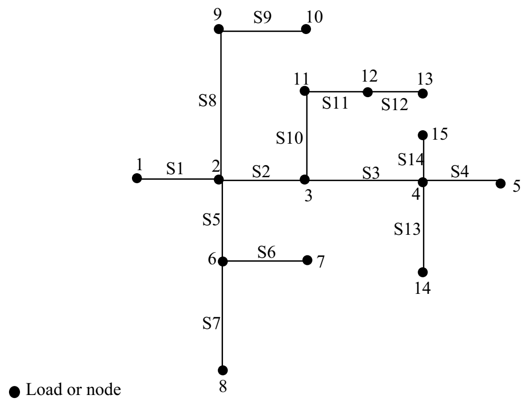


Fig. 3 Structure of the IEEE 15-node system

active power losses and voltage deviation by using the MIP (Mixed Integer Programming) solver while maintaining priority consumers supplied with power electric energy.

*Step 8***:** Show the result

Step 9: Start over at the next period

We repeat the above steps in the next period.

Results and discussion

The program is written in GAMS 23.5. The computer characteristics are: Processor: 1.70 GHz; RAM: 4.00 GB; OS: 64-bit WINDOWS 10.

In this paper, we use three standard IEEE system: 15, 33 and 69 bus.

IEEE test 15-node system

Presentation of the structure

The structure of the IEEE 15 node network used is given in Fig. 3.

The RMS value of the voltage at node 1 of the network is 12.66 kV. The characteristics of the power lines of the network are borrowed from [15]. The priority consumers are 6, 7 and 8.

In this study the day is divided into 24 periods of one hour duration and the maximum number of switching operations is 10.

The active powers of the load in each period are borrowed from [10].

Table 1 presents the results without and after reconfiguration in period 1 of the 15-node system.

Table 2 presents the results without and after reconfiguration in period 2 of the 15-node system.

Table 3 presents the summary of the results of the dynamic reconfiguration of the 15-node system in each period.

The profile of the active and reactive load powers of the 24 h of the 15-node system is given in Fig. 4.

Table 1 Results at period 1 of IEEE 15-node system

Maximum active power available from the source: 2500 kW			
Maximum reactive power available from the source: 1700 kVAr			
	Without reconfiguration	**After reconfiguration**	**Reduction (%)**
Total active power load (kW)	4554.0	1710.0	62.45
Total reactive power load (kVAr)	3415.5	1278.0	62.58
Open switches	No open switches	S2	/
Active power losses (kW)	0*	82.169	/
Reactive power losses (kVAr)	0*	69.633	/
Vmin (p.u.)	0*	0.9455 (node 8)	/
V_{de} (p.u.)	1*	0.0545	/
Supplied node	No	1, 2, 6, 7, 8, 9, 10	/
SAIFI (failure/day)	1	0.571	42.9
SAIDI (h/day)	1	0.571	42.9

*This situation is due to the fact that there is an interruption in the supply of electrical energy because the available power is insufficient

Table 2 Results at period 2 of the IEEE 15-node system

Maximum active power available from the source: 5000 kW			
Maximum reactive power available from the source: 3500 kVAr			
	Without reconfiguration	**After reconfiguration**	**Reduction (%)**
Total active power load (kW)	4305.0	1614.0	62.50
Total reactive power load (kVAr)	3228.75	1212.0	62.46
Open switches	No open switches	S2	/
Active power losses (kW)	384.67	66.937	82.59
Reactive power losses (kVAr)	357.37	56.835	84.09
Vmin (p.u.)	0.8752 (node 13)	0.9508 (node 8)	/
V_{de} (p.u.)	0.1248	0.0492	60.57
Supplied node	1 to15	1, 2, 6, 7, 8, 9, 10	/
SAIFI (failure/day)	0	0.571	/
SAIDI (h/day)	0	0.571	/

Figure 5 shows the variation of the active and reactive powers available from the source and those of the load without reconfiguration for 24 h of the 15-node system.

Figure 6 gives the variation of the active and reactive power losses without and after for 24 h reconfiguration of the 15-node system.

Figure 7 gives the minimum voltage profile of the nodes for 24 h and that at period 1 of the 15-node system.

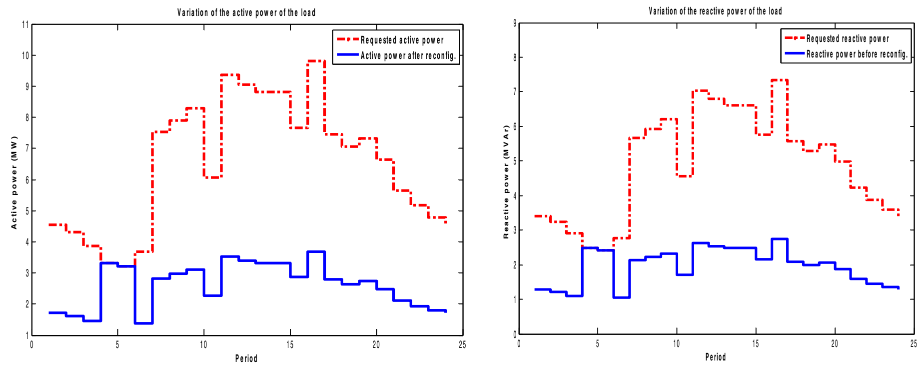
Figure 8 shows the changes in switch states for a dynamic reconfiguration for 24 h of the 15-node system.

Table 1 presents the results without and after reconfiguration in period 1. The active and reactive power of the load are, respectively, 4554.0 kW and 3415.5 kVAr. Initially, all switches are ON and the maximum active and reactive powers available are, respectively, 2500 kW and 1700 kVAr. If there is no reconfiguration, there will be an interruption in the supply of electrical energy. The load must therefore be reduced by reconfiguring the

Table 3 Results of the dynamic reconfiguration of the IEEE 15- node system

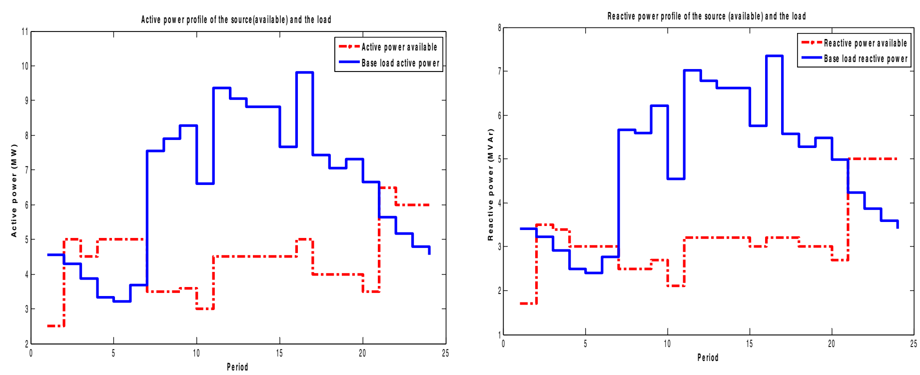
Period	Active power load (kW)	SAIFI (failure/day)	Without reconfiguration					After reconfiguration					
			Active power losses (kW)	SAIDI (h/day)	Open switches	Vmin (p.u.)	V_{de} (p.u.)	Active power losses (kW)	SAIFI (fail./day)	Open switches	Vmin (p.u.)	V_{de} (p.u.)	SAIDI (h/day)
1	4554.0	1	0*	1	No	0*	1*	80.169	0.571	S2	0.9455	0.0545	0.571
2	4305.0	0	384.67	0	No	0.8752	0.1248	66.937	0.571	S2	0.9508	0.0492	0.571
3	3876.0	0	312.27	0	No	0.8874	0.1126	56.431	0.571	S2	0.9548	0.0452	0.571
4	3326.0	0	230.35	0	No	0.9030	0.0970	230.35	0	No	0.9030	0.0970	0
5	3205.0	0	213.98	0	No	0.9065	0.0935	213.98	0	No	0.9065	0.0935	0
6	3693.0	0	283.65	0	No	0.8925	0.1075	50.779	0.571	S2	0.9571	0.0429	0.571
7	7542.0	1	0*	1	No	0*	1*	204.39	0.571	S2	0.9141	0.0859	0.571
8	7909.0	1	0*	1	No	0*	1*	229.48	0.571	S2	0.9090	0.0910	0.571
9	8279.0	1	0*	1	No	0*	1*	232.13	0.571	S2	0.9086	0.0914	0.571
10	6067.0	1	0*	1	No	0*	1*	137.05	0.571	S2	0.9296	0.0704	0.571
11	9369.0	1	0*	1	No	0*	1*	278.41	0.571	S2	0.9000	0.1000	0.571
12	9054.0	1	0*	1	No	0*	1*	276.88	0.571	S2	0.9001	0.0999	0.571
13	8823.0	1	0*	1	No	0*	1*	265.53	0.571	S2	0.9022	0.0978	0.571
14	8823.0	1	0*	1	No	0*	1*	265.53	0.571	S2	0.9022	0.0978	0.571
15	7670.0	1	0*	1	No	0*	1*	205.74	0.571	S2	0.9139	0.0861	0.571
16	9801.0	1	0*	1	No	0*	1*	280.96	0.571	S2	0.9000	0.1000	0.571
17	7440.0	1	0*	1	No	0*	1*	201.46	0.571	S2	0.9148	0.0852	0.571
18	7049.0	1	0*	1	No	0*	1*	187.44	0.571	S2	0.9178	0.0822	0.571
19	7317.0	1	0*	1	No	0*	1*	196.50	0.571	S2	0.9157	0.0843	0.571
20	6643.0	1	0*	1	No	0*	1*	156.41	0.571	S2	0.9248	0.0752	0.571
21	5651.0	0	659.79	0	No	0.8378	0.1622	125.52	0.571	S2	0.9326	0.0674	0.571
22	5163.0	0	551.68	0	No	0.8513	0.1487	102.38	0.571	S2	0.9391	0.0609	0.571
23	4793.0	0	476.04	0	No	0.8616	0.1384	85.872	0.571	S2	0.9443	0.5570	0.571
24	4554.0	0	430.09	0	No	0.8683	0.1317	82.169	0.571	S2	0.9455	0.0545	0.571
Total	–	15	3542.52	15	–	–	–	4212.49	12.56	–	–	–	12.56
Average	–	0.625	147.605	0.625	–	–	–	175.52	0.523	–			0.523

* This situation is due to the fact that there is an interruption in the supply of electrical energy because the available power is insufficient



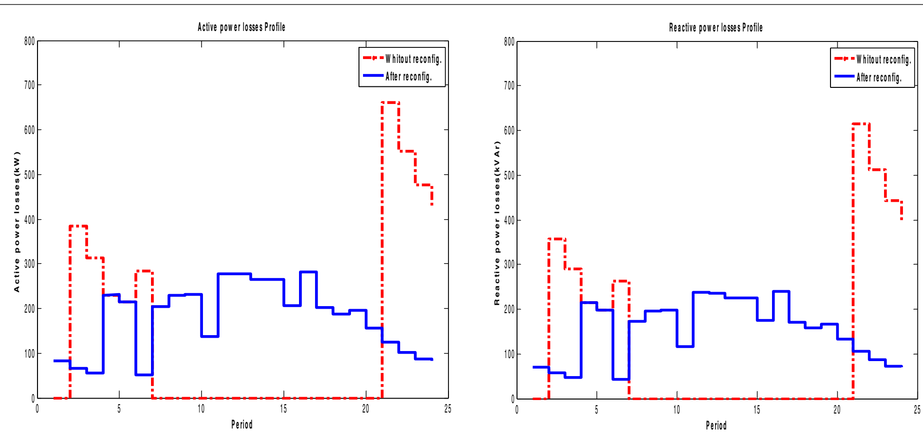
(a) **(b)**

Fig. 4 Load power variation for 24 h of the IEEE 15-node system: **a** Active power **b** Reactive power



(a) **(b)**

Fig. 5 Variation of the available power of the source and the load power for 24 h of the IEEE 15-node system: **a** Active power **b** Reactive power



(a) **(b)**

Fig. 6 Power losses variation for 24 h of the IEEE 15- node system: **a** Active power losses, **b** Reactive power losses

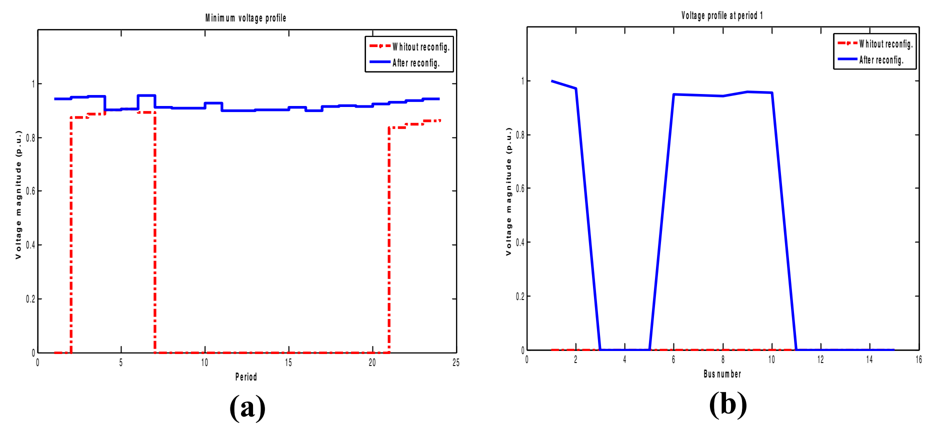


Fig. 7 Voltage Profile of the 15-node system without and after reconfiguration: **a** Minimum voltage **b** Voltage at period 1

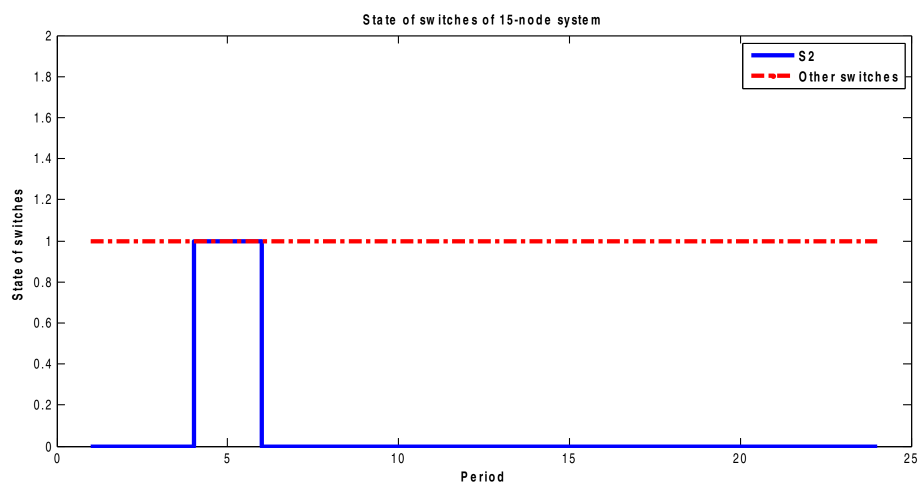


Fig. 8 Dynamic changes in switch states for 24 h of the IEEE 15-node system

network. After reconfiguration, S2 is OFF and the active power of the load becomes 1710.0 kW, a reduction of 62.45% and the reactive power 1278.0 kVAr, a reduction of 62.58%. The active and reactive online power losses are, respectively, 82.169 kW and 69.633 kVAr. The minimum voltage is 0.9455 p.u. (node 8) and the voltage deviation is 0.0545 p.u. Priority consumers (6, 7 and 8) are always supplied. After reconfiguration, the nodes that have the energy are 1, 2, 6, 7, 8, 9 and 10. Without reconfiguration, the SAIFI is 1 failure/day and the SAIDI is 1 h/day. After reconfiguration, the SAIFI is 0.571 failure/day, a reduction of 42.9% and the SAIDI is 0.571 h/day, a reduction of 42.9%. There is a reduction in the frequency and duration of the interruption after reconfiguration. We can say that the new configuration improves the reliability of the system.

Table 2 presents the results before and after reconfiguration in period 2. Initially, all the switches are ON and the active and reactive power of the load are, respectively, 4305.0 kW and 3228.75 kVAr. The maximum active and reactive powers available are, respectively, 5000 kW and 3500 kVAr. The available power is sufficient. Without reconfiguration, the active and reactive power losses are 384.67 kW and 357.37 kVAr, respectively. The minimum voltage is 0.8752 p.u. (node 13). This voltage is unacceptable. The system must be reconfigured to provide a tolerable voltage to consumers. The voltage deviation is 0.1248 p.u. After reconfiguration, the active power of the load becomes 1614.0 kW, a reduction of 62.50% and the reactive power 1212.0 kVAr, a reduction of 62.46%. Active power losses are 66,937 kW, a reduction of 82.59% and reactive 56,835 kVAr, a reduction of 84.09%. The minimum voltage is 0.9508 p.u. (node 8) and the voltage deviation 0.0492 p.u., a reduction of 60.57%. After reconfiguration, the nodes that have the energy are 1, 2, 6, 7, 8, 9 and 10. Without reconfiguration, the SAIFI is 0 failure/day and the SAIDI is 0 h/day. After reconfiguration, the SAIFI is 0.571 failure/day.

Table 3 shows a summary of the results of the network of 15 nodes per period over 24 h. At intervals 1, 7 to 20, if there is no reconfiguration of the network, there will be an interruption in the supply of electrical energy. During a day, after reconfiguration, the minimum voltage is acceptable and the priority loads are always supplied. Periods 1 and 24 have the same load power but in period 1, the available power is insufficient, it is imperative to reduce the load. But at period 24, the available power is sufficient but the power losses are significant and the minimum voltage unacceptable. The system must be reconfigured to minimize power losses and voltage deviation. In periods 4 and 5, the optimal configuration corresponds to the initial topology. All consumers are powered and voltages are normal. Subscribers are satisfied with the supply of electrical energy. In the other periods, the optimal topology obtained proposes the opening of the switch S2. Without reconfiguration, the average SAIFI for 24 h is 0.625 failure/day and the average SAIDI for 24 h is 0.625 h/day. After reconfiguration, the average SAIFI for 24 h is 0.523 failure/day, a reduction of 16.32% and the average SAIDI for 24 h is 0.523 h/day, a reduction of 16.32%. There is a reduction in the frequency and duration of the interruption after reconfiguration for 24 h. We can say that the technique proposed in this study gives optimal configurations which improves the reliability of the network.

Figure 3 shows the evolution of the active and reactive power of the load for 24 h. It presents the profile of the power required by the load and that absorbed after reconfiguration. When the energy available is sufficient, the power initially requested corresponds to that after reconfiguration of the system (periods 4 and 5). When the available energy is insufficient (the other periods), the load is reduced. Period 16 is one that has a higher call for power.

Figure 5 shows the variation of the power available and that initially requested by the load. During periods 2 to 7 and 21 to 24, the available power is sufficient. But during the other periods, there is insufficient energy. The highest available power is at period 21.

Figure 6 shows power losses profile for 24 h. Before reconfiguration, in periods 2, 3, 6 and 21 the power losses are significant. After reconfiguration, they are minimized. The power losses before and after reconfiguration are identical to the periods 4 and 5 because the optimal configuration corresponds to the initial topology. In other periods, there is an interruption in the supply of electrical energy if there is no reconfiguration.

Figure 7 shows the variation of the minimum voltage of the nodes before and after reconfiguration and the profile of the tension in period 1. The reconfiguration increases the minimum tension by period consequently minimizes the deviation in tension. In period 1, after reconfiguration nodes 3, 4, 5, 11, 12, 13, 14, 15 are not supply.

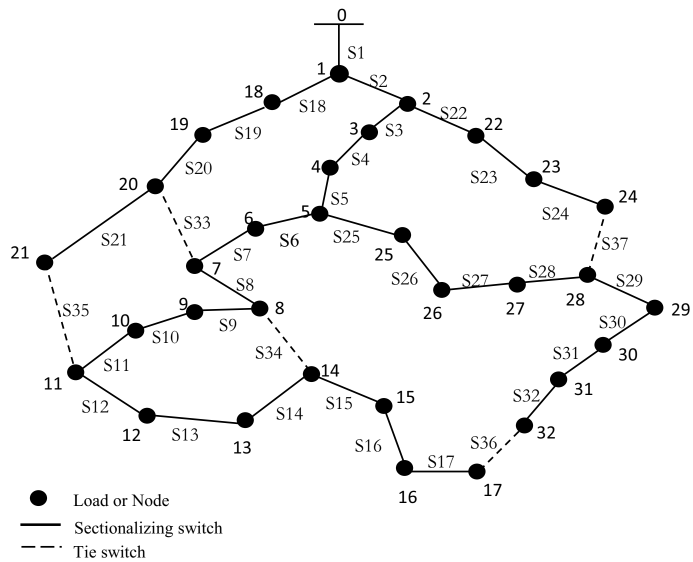


Fig. 9 Structure of the IEEE 33-node system

Table 4 Results at period 1 of IEEE 33-node system

Maximum active power available from the source: 5000 kW			
Maximum reactive power available from the source: 3500 kVAr			
	Without reconfiguration	**After reconfiguration**	**Reduction (%)**
Total active power load (kW)	3635.0	3635.0	0
Total reactive power load (kVAr)	2726.25	2726.25	0
Open switches	S33, S34, S35, S36, S37	S6, S8, S13, S28, S36	/
Active power losses (kW)	185.72	126.56	31.85
Reactive power losses (kVAr)	137.67	130.05	5.53
Vmin (p.u.)	0.8867 (node 17)	0.9291 (node 17)	/
V_{de} (p.u.)	0.1133	0.0709	37.42
Supplied node	0 to 32	0 to 32	/
SAIFI (failure/day)	0	0	/
SAIDI (h/day)	0	0	/

Figure 8 shows the chronological change in switch states. It shows that during the dynamic reconfiguration over a day there are two switching operations of branches or switches. Only switch S2 changes state. Indeed, S2 is closed during periods 4 and 5 and open elsewhere. S2 switches twice.

IEEE test 33-node system

Presentation of the structure

The structure of the IEEE 33 node network used is given in Fig. 9.

The RMS value of the voltage at node 0 of the network is 12.66 kV. The characteristics of the power lines of the network are borrowed from [16]. The priority consumers are 15, 22, 26 and 30.

Table 5 Results at period 6 of IEEE 33-node system

Maximum active power available from the source: 2500 kW			
Maximum reactive power available from the source: 1200 kVAr			
	Without reconfiguration	**After reconfiguration**	**Reduction (%)**
Total active power load (kW)	3849.0	2390.0	37.90
Total reactive power load (kVAr)	2886.75	1050.6	63.60
Open switches	S33, S34, S35, S36, S37	S5, S6, S7, S8, S9, S12, S15, S18, S19, S35	/
Active power losses (kW)	0*	76.282	/
Reactive power losses (kVAr)	0*	52.815	/
Vmin (p.u.)	0*	0.9512 (node 5)	/
V_{de} (p.u.)	1*	0.0488	/
Supplied node	No	0, 1, 2, 3, 4, 5, 15, 16, 17, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	/
SAIFI (failure/day)	1	0.406	59.4
SAIDI (h/day)	3	1.218	59.4

*This situation is due to the fact that there is an interruption in the supply of electrical energy because the available power is insufficient

In this study the day is divided into 8 periods of 3 h duration and the maximum number of switching operations is 20.

The active powers of the load in each period are borrowed from [3].

Table 4 presents the results without and after reconfiguration in period 1 of the 33-node system.

Table 5 presents the results without and after reconfiguration in period 6 of the 33-node system.

Table 6 presents the summary of the results of the dynamic reconfiguration of the 33-node system in each period.

The profile of the active and reactive load powers for 24 h of the 33-node system is given in Fig. 10.

Figure 11 shows the variation of the active and reactive powers available from the source and those of the load without reconfiguration for 24 h of the 33-node system.

Figure 12 shows the variation in active and reactive power losses without and after reconfiguration for 24 h of the 33-node system.

Figure 13 shows the minimum voltage profile of the nodes for 24 h and that for period 1 of the 33-node system.

Figure 14 presents the voltage profile in period 6 and the change in switch states for a dynamic reconfiguration for 24 h of the 33-node system.

Table 4 presents the results in period 1 of the 33-node system. The active and reactive powers available are, respectively, 5000 kW and 3500 kVAr. Initially, S33, S34, S35, S36, S37 are open and the active and reactive powers of the load are, respectively, 3635.0 kW and 2726.25 kVAr. Since the available energy is sufficient, the reconfiguration must maintain the same charge to satisfy consumers. Without the reconfiguration, the active and reactive losses are, respectively, 185.72 kW and 137.67 kVAr, the minimum voltage at the nodes is 0.8867 p.u. (node 17) and the voltage deviation is 0.1133 p.u. These power losses are significant and this minimum voltage is unacceptable. It is therefore necessary to

Table 6 Results of the dynamic reconfiguration of the IEEE 33- node system

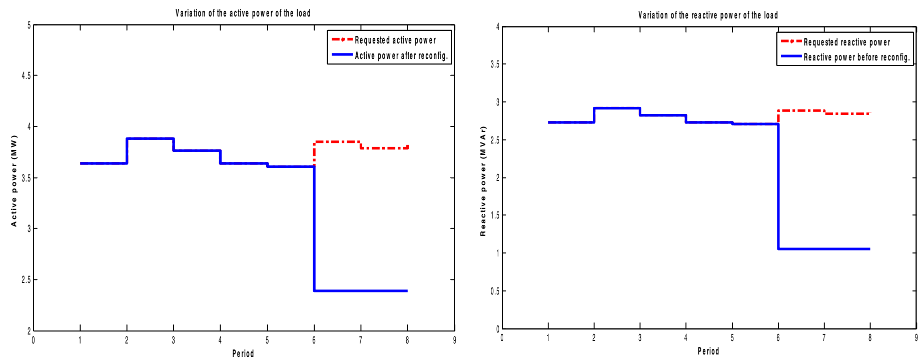
Period	Active power load (kW)	SAIFI (failure/day	Without reconfiguration					After reconfiguration					
			Active losses power (kW)	SAIDI (h/day)	Open switches	Vmin (p.u.)	V_{de}(p.u.)	Active losses power (kW)	SAIFI (fail./day)	Open switches	Vmin (p.u.)	V_{de}(p.u.)	SAIDI (h/day)
1	3635.0	0	185.72	0	(a)	0.8867	0.1133	126.56	0	(b)	0.9291	0.0709	0
2	3883.0	0	219.97	0	(a)	0.8746	0.1254	148.13	0	(b)	0.9221	0.0779	0
3	3766.0	0	203.41	0	(a)	0.8803	0.1197	137.70	0	(b)	0.9255	0.0745	0
4	3638.0	0	186.11	0	(a)	0.8865	0.1135	126.81	0	(b)	0.9290	0.0710	0
5	3605.0	0	181.79	0	(a)	0.8881	0.1119	124.10	0	(b)	0.9299	0.0701	0
6	3849.0	1	0*	3	(a)	0*	1*	76.282	0.406	(c)	0.9512	0.0488	1.218
7	3788.0	1	0*	3	(a)	0*	1*	76.282	0.406	(c)	0.9512	0.0488	1.218
8	3825.0	1	0*	3	(a)	0*	1*	76.282	0.406	(c)	0.9512	0.0488	1.218
Total	–	3	977	9	–	–	–	892.146	1.218	–	–	–	3.654
Average		0.375	122.12	1.125	–	–	–	111.518	0.152	–	–	–	0.456

* This situation is due to the fact that there is an interruption in the supply of electrical energy because the available power is insufficient

(a): S33, S34, S35, S36, S37

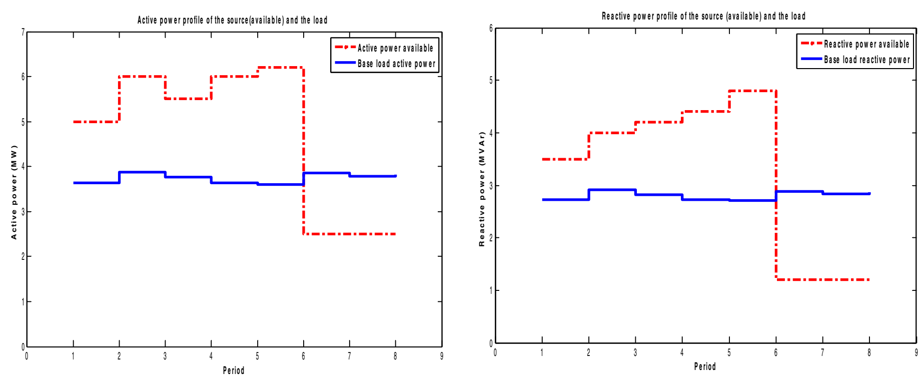
(b): S6, S8, S13, S28, S36

(c): S5, S6, S7, S8, S9, S12, S15, S18, S19, S35



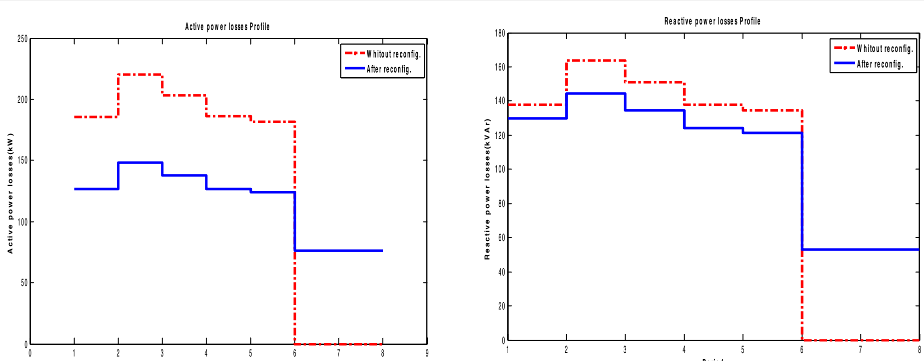
(a) (b)

Fig. 10 Load power variation for 24 h of the IEEE 33-node system: **a** Active power **b** Reactive power



(a) (b)

Fig. 11 Variation of the available power of the source and the load power for 24 h of the IEEE 33-node system: **a** Active power **b** Reactive power



(a) (b)

Fig. 12 Power losses variation for 24 h of the IEEE 33-node system: **a** Active power losses, **b** Reactive power losses

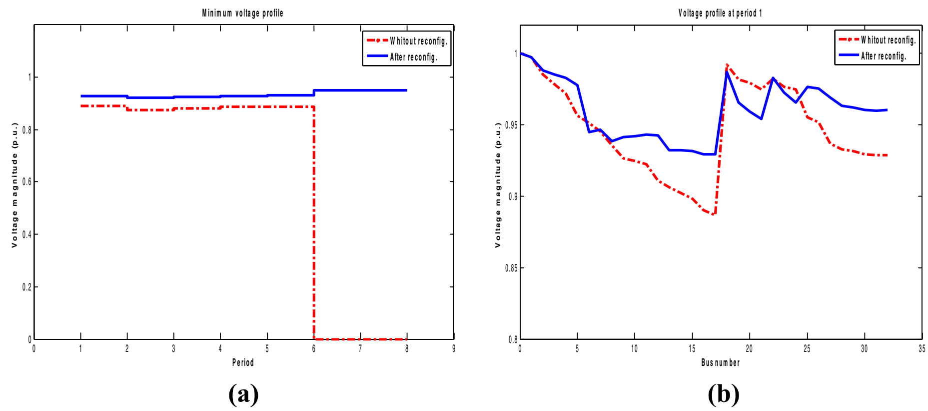


Fig. 13 Voltage Profile of the 33-node system before and after reconfiguration: **a** Minimum voltage **b** Voltage at period 1

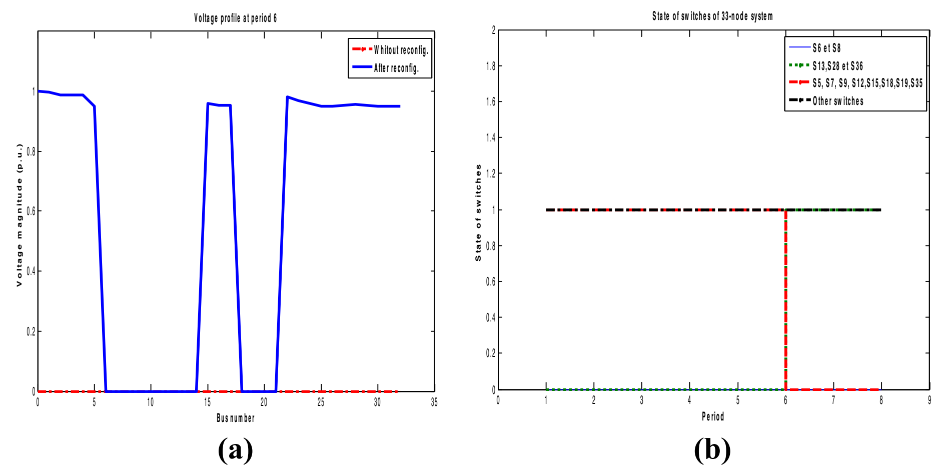


Fig. 14 **a** Voltage profile at period 6, **b** Dynamic changes in switch states for 24 h of the IEEE 33-node system

reconfigure the network. After reconfiguration, the load power is the same, the switches S6, S8, S13, S28 and S36 are open. Active and reactive power losses are, respectively, 126.56 kW, a reduction of 31.85% and 130.05 kVAr, a reduction of 5.53%. The minimum voltage becomes acceptable and equal to 0.9291 p.u. (node 17) and the voltage deviation is 0.0709 p.u., a reduction of 37.42%. All consumers are supplied and satisfied. Without reconfiguration, the SAIFI is 0 failure/day and the SAIDI is 0 h/day. After reconfiguration, the SAIFI is 0 failure/day and the SAIDI is 0 h/day.

Table 5 presents the results of the 33-node system in period 6. The active and reactive powers available are, respectively, 2500 kW and 1200 kVAr. Initially, S33, S34, S35, S36, S37 are open and the active and reactive power of the load are, respectively, 3849.0 kW and 2886.75 kVAr, there will be an interruption in the supply of electrical energy because the available energy is insufficient. After reconfiguration, the load is reduced. The active and reactive powers of the load become, respectively, 2390.0 kW, a reduction of 37.90% and 1050.6 kVAr, a reduction of 63.60%. Switches S5, S6, S7, S8, S9, S12, S15, S18, S19 and S35 are open. Active and reactive power losses are, respectively, 76.282 kW and 52.815 kVAr. The minimum voltage is 0.9512 p.u. (node 5) and the voltage deviation 0.0488 p.u. The consumers 1, 2, 3, 4, 5, 15, 16, 17, 22, 23, 24, 25, 26, 27, 28, 29, 30 are supplied. Without reconfiguration, the SAIFI is 1 failure/day and the SAIDI is 3 h/day. After reconfiguration, the SAIFI is 0.406 failure/day, a reduction of 59.4% and the SAIDI is 1.218 h/day, a reduction of 59.4%. There is a reduction in the frequency and duration of the interruption after reconfiguration. We can say that the new configuration improves the reliability of the system.

Table 6 presents a summary of the results of the dynamic reconfiguration of the 33-node system for 24 h. From period 1 to 5, the optimal configuration is S6, S8, S13, S28 and S36 OFF and from period 6 to 8 the optimal topology is S5, S6, S7, S8, S9, S12, S15, S18, S19 and S35 OFF. The dynamic reconfiguration of the network over a day leads to 11 switching operations of the branches or switches, which is less than the fixed limit which is 20. Without reconfiguration, the average SAIFI for 24 h is 0.375 failure/day and the average SAIDI for 24 h is 1.125 h/day. After reconfiguration, the average SAIFI for 24 h is 0.152 failure/day, a reduction of 59.46% and the average SAIDI for 24 h is 0.456 h/day, a reduction of 59.46%. There is a reduction in the frequency and duration of the interruption after reconfiguration for 24 h. We can say that the technique proposed in this study gives optimal configurations which improves the reliability of the network.

Figure 10 shows the evolution of the active and reactive powers requested by the load and those called after reconfiguration. From period 1 to 5, the energy available is sufficient, the power of the load corresponds to that absorbed initially. But from period 6 to 8, there is a lack of energy, the load is reduced to satisfy certain consumers.

Figure 11 shows the variation of the available power and that of the load before reconfiguration. It is found that the energy available is sufficient from period 1 to 5. In period 6 to 8, this energy is insufficient.

Figure 12 shows the power losses profile per period for 24 h. Initially, from period 1 to 5, the power losses are significant. After reconfiguration, these power losses are reduced. From period 6 to 8, there is an interruption in the supply of electrical energy if there is no reconfiguration of the network.

Figure 13 shows the variation of the minimum voltage per period and the voltage profile at the level of the nodes at period 1. Before and after reconfiguration, the voltage at node 17 is that which is minimum. After reconfiguration the voltage level of the nodes is satisfactory for consumers.

Figure 14 shows the evolution of the voltage in period 6 and the chronological changes of the state of the switches for 24 h. It is noted that after reconfiguration the nodes without voltage are 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19, 20 and 21. The dynamic change in the switches shows that the number of switching operations is 11 on a day.

IEEE test 69-node system

Presentation of the structure

The structure of the IEEE 69 node network used is given in Fig. 15.

The RMS value of the voltage at node 1 of the network is 12.66 kV. The position of each switch are borrowed from [17] and the characteristics of the power lines are the same as those used in [18].

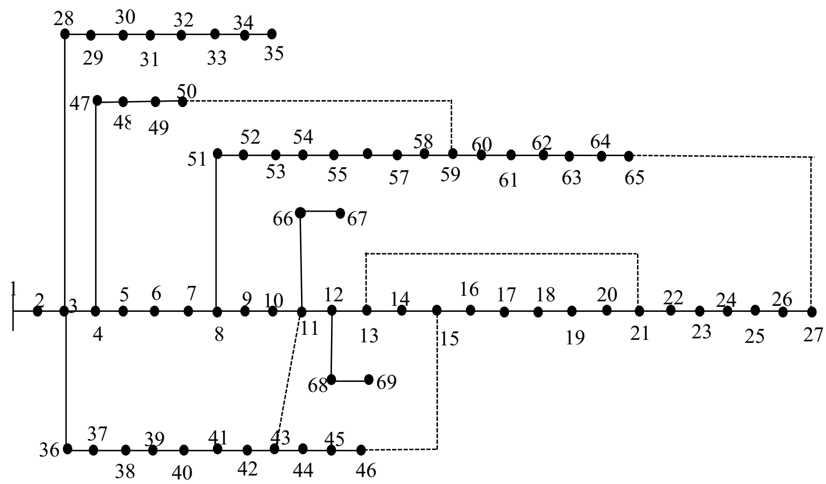


Fig. 15 Structure of the IEEE 69 bus

Table 7 Results at period 1 of IEEE 69-node system

Maximum active power available from the source: 4000 kW			
Maximum reactive power available from the source: 3500 kVAr			
	Without reconfiguration	**After reconfiguration**	**Reduction (%)**
Total active power load (kW)	2967.0	2967.0	0
Total reactive power load (kVAr)	2555.0	2555.0	0
Open switches	S69, S70, S71, S72, S73	S14, S57, S61, S69, S70	/
Active power losses (kW)	102.58	93.85	8.51
Reactive power losses (kVAr)	56.148	52.285	6.88
Vmin (p.u.)	0.9744 (node 17)	0.9766 (node 14)	/
V_{de} (p.u.)	0.0256	0.0234	8.59
Supplied node	1 to 69	1 to 69	/
SAIFI (failure/day)	0	0	/
SAIDI (h/day)	0	0	/

The priority consumers are 28 and 36.

In this study, the day is divided into 8 periods of 3 h duration and the maximum number of switching operation is 40.

Table 7 presents the results without and after reconfiguration in period 1 of the 69-node system.

Table 8 presents the results without and after reconfiguration in period 5 of the 69-node system.

Table 9 presents the summary of the results of the dynamic reconfiguration of the 69-node system in each period.

The profile of the active and reactive powers of the 24-h load of the 69-node system is given in Fig. 16.

Figure 17 shows the variation of the active and reactive powers available from the source and those of the load without reconfiguration for 24 h of the 69-node system.

Table 8 Results at period 5 of IEEE 69-node system

Maximum active power available from the source: 2000 kW			
Maximum reactive power available from the source: 1000 kVAr			
	Without reconfiguration	**After reconfiguration**	**Reduction (%)**
Total active power load (kW)	7000.0	412.0	94.11
Total reactive power load (kVAr)	5250.0	312.0	94.05
Open switches	S69, S70, S71, S72, S73	S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S16, S18, S20, S28, S29, S30, S31, S32, S33, S34, S36, S37, S38, S40, S72, S73	/
Active losses power (kW)	0*	0.0038	/
Reactive losses power (kVAr)	0*	0.0281	/
Vmin (p.u.)	0*	0.9999 (node 36)	/
V_{de} (p.u.)	1*	0.0001	/
Supplied node	No	1, 2, 3, 28, 36	/
SAIFI (failure/day)	1	0.941	5.9
SAIDI (h/day)	3	2.823	5.9

* This situation is due to the fact that there is an interruption in the supply of electrical energy because the available power is insufficient

Figure 18 shows the variation in active and reactive power losses without and after reconfiguration for 24 h of the 69-node system.

Figure 19 gives the minimum voltage profile of the nodes for 24 h and that for period 1 of the 69-node system.

Figure 20 shows the voltage profile at period 5 and the changes in switch states for dynamic reconfiguration for 24 h of the 69-node system.

Table 7 presents the results in period 1 of the 69-node system. The active and reactive powers available are, respectively, 4000 kW and 3500 kVAr. Initially, S69, S70, S71, S72 and S73 are open and the active and reactive powers of the load are, respectively, 2967 kW and 2555 kVAr. Active and reactive power losses are, respectively, 102.58 kW and 56.148 kVAr, the minimum voltage is 0.9744 p.u. (node17) and the voltage deviation is 0.0256 p.u. The availability of energy avoids the reduction in the load. After reconfiguration, S14, S57, S61, S69, S70 are OFF. Active and reactive power losses are, respectively, 93.85 kW, a reduction of 8.51% and 52.285 kVAr, a reduction of 6.88%. The minimum voltage is 0.9766 (node 14) and the voltage deviation is 0.0234, a reduction of 8.59%. Whitout reconfiguration, the SAIFI is 0 failure/day and the SAIDI is 0 h/day. After reconfiguration, the SAIFI is 0 failure/day and the SAIDI is 0 h/day.

Table 8 presents the results in period 5 of the 69-node system. The active and reactive powers available are, respectively, 2000 kW and 1000 kVAr. Initially, S69, S70, S71, S72 and S73 are open and the active and reactive powers of the load are, respectively, 7000 kW and 5250 kVAr. Insufficient energy means reducing the load. If there is no reconfiguration, there will be an interruption in the supply of electrical energy. After reconfiguration, switches S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S15, S16, S18, S20, S28, S29, S30, S31, S32, S33, S34, S36, S37, S38, S40, S72, S73 are open. The active and reactive powers of the load are reduced by 94.11% and 94.05%, respectively. Active and reactive power losses are low and are, respectively, 0.0038 kW and 0.0281 kVAr. The minimum voltage is 0.9999 p.u. (node 36)

Table 9 Results of the dynamic reconfiguration of the IEEE 69-node system

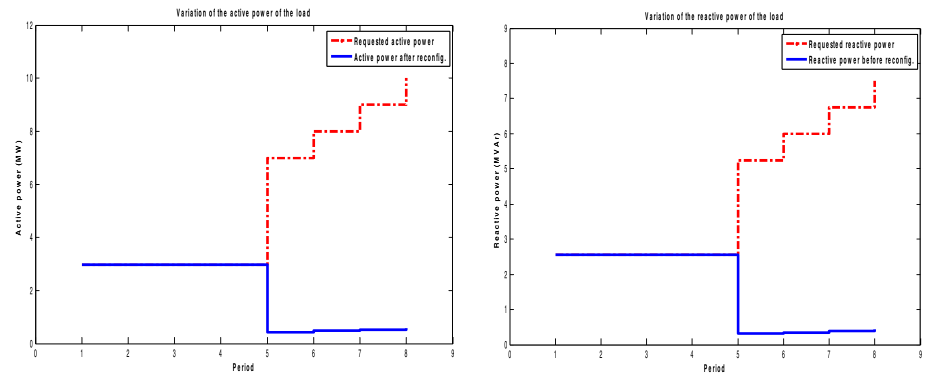
Period	Active power load (kW)	SAIFI (failure/ day	Without reconfiguration					After reconfiguration					
			Active losses power (kW)	SAIDI (h/day)	Open switches	Vmin (p.u.)	V_{de}(p.u.)	Active losses power (kW)	SAIFI (fail./day	Open switches	Vmin (p.u.)	V_{de}(p.u.)	SAIDI (h/day)
1	2967.0	0	102.58	0	(c)	0.9744	0.0254	93.85	0	(d)	0.9766	0.0234	0
2	2967.0	0	102.58	0	(c)	0.9744	0.0254	93.85	0	(d)	0.9766	0.0234	0
3	2967.0	0	102.58	0	(c)	0.9744	0.0254	93.85	0	(d)	0.9766	0.0234	0
4	2967.0	0	102.58	0	(c)	0.9744	0.0254	93.85	0	(d)	0.9766	0.0234	0
5	7000.0	1	0*	3	(c)	0*	1*	0.0038	0.941	(e)	0.9999	0.0001	2.823
6	8000.0	1	0*	3	(c)	0*	1*	0.0045	0.941	(e)	0.9999	0.0001	2.823
7	9000.0	1	0*	3	(c)	0*	1*	0.0052	0.941	(e)	0.9999	0.0001	2.823
8	10,000.0	1	0*	3	(c)	0*	1*	0.0060	0.941	(e)	0.9999	0.0001	2.823
Total	–	4	410.32	12	–-	–	–	375.41	3.764	–	–	–	11.292
Ave-rage		0.333	51.29	1.5	–	–	–	46.92	0.470	–	-	–	1.411

* This situation is due to the fact that there is an interruption in the supply of electrical energy because the available power is insufficient

(c): S69, S70, S71, S72, S73

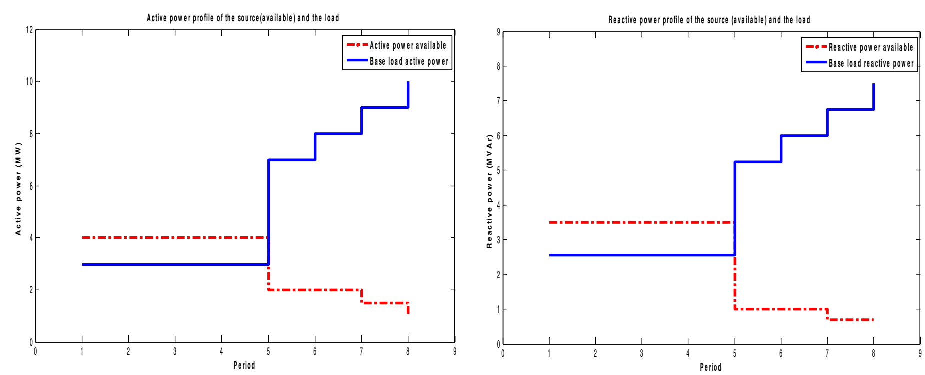
(d): S14, S57, S61, S69, S70

(e): S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S16, S18, S20, S28, S29, S30, S31, S32, S33, S34, S36, S37, S38, S40, S72, S73



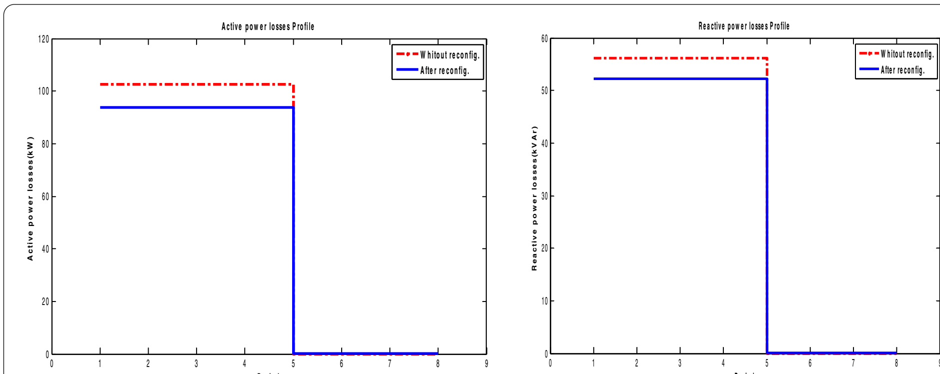
(a) (b)

Fig. 16 Load power variation for 24 h of the IEEE 69-node system: **a** Active power **b** Reactive power



(a) (b)

Fig. 17 Variation of the available power of the source and the load power for 24 h of the IEEE 69-node system: **a** Active power **b** Reactive power



(a) (b)

Fig. 18 Power losses variation for 24 h of the IEEE 69- node system: **a** Active power losses, **b** Reactive power losses

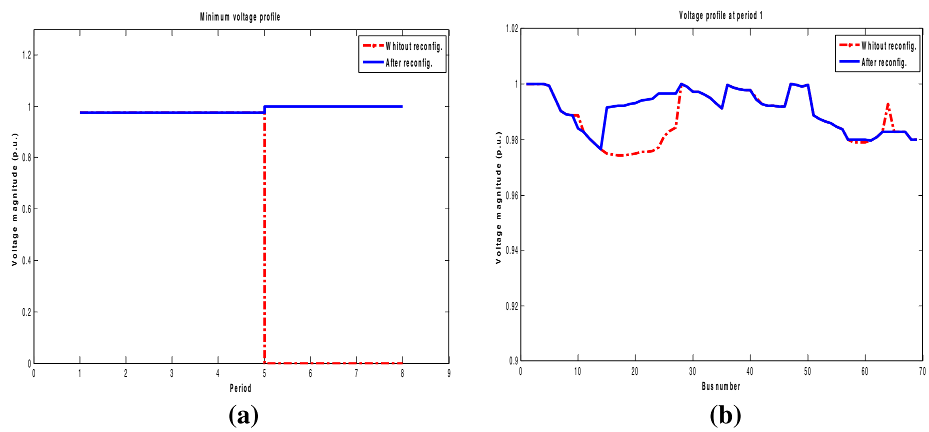


Fig. 19 Voltage Profile of the 69-node system before and after reconfiguration: **a** Minimum voltage **b** Voltage at period 1

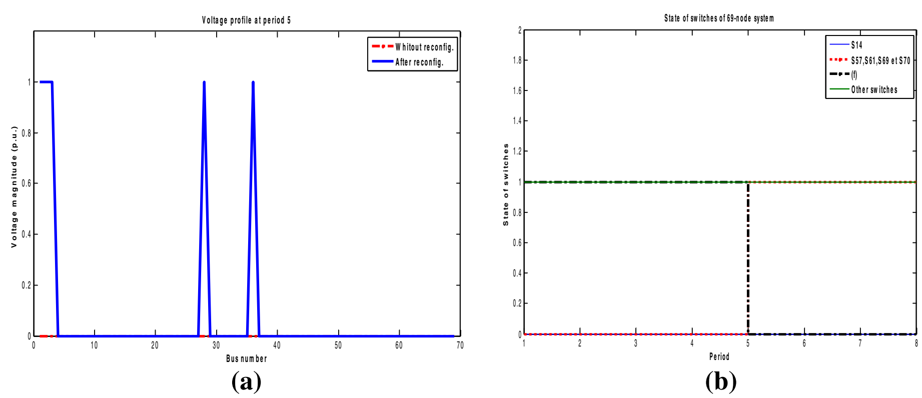


Fig. 20 **a** Voltage profile at period 6, **b** Dynamic changes in switch states for 24 h of the IEEE 69-node system. (f): S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S15, S16, S18, S20, S28, S29, S30, S31, S32, S33, S34, S36, S37, S38, S40, S72, S73

and the voltage deviation is 0.0001 p.u. The nodes supplied are 1, 2, 3, 28 and 36. Without reconfiguration, the SAIFI is 1 failure/day and the SAIDI is 3 h/day. After reconfiguration, the SAIFI is 0.941 failure/day, a reduction of 5.9% and the SAIDI is 2.823 h/day, a reduction of 5.9%. There is a reduction in the frequency and duration of the interruption after reconfiguration. We can say that the new configuration improves the reliability of the system.

Table 9 presents a summary of the results of the dynamic reconfiguration of the 69-node system for one day. From period 1 to 4, the optimal topology is S14, S57, S61, S69 and S70 OFF and from period 5 to 8 the optimal topology is S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S15, S16, S18, S20, S28, S29, S30, S31, S32, S33, S34, S36, S37, S38, S40, S72 and S73 OFF. Dynamic reconfiguration of the network for 24 h. involves 32 switching operations of branches or switches, which is less than the fixed limit which is 40.

Figure 16 shows the evolution of the active and reactive powers requested by the load and those called after reconfiguration. From period 1 to 4, the power available at the source is sufficient, the power of the load corresponds to that absorbed at the start. But from period 5 to 8, there is a lack of energy, the load is reduced to satisfy certain consumers, especially the priority ones.

Figure 17 shows the profile of the available power and that of the initial load. The available energy is sufficient from period 1 to 4. In periods 5 to 8, this power is insufficient.

Figure 18 presents the profile of power losses per period for one day. Initially, from period 1 to 4, the power losses are significant. After reconfiguration, these power losses are reduced. From period 5 to 8, there is an interruption in the supply of electrical energy if there is no reconfiguration of the network.

Figure 19 shows the profile of the minimum voltage per period and the voltage profile at node level in period 1. Initially, node 17 has the minimum network voltage and after reconfiguration, the voltage at node 14 is that which is minimal.

Figure 20 shows the evolution of the voltage in period 6 and the dynamic change in the state of the switches for one day. After reconfiguration the nodes supplied are 1, 2, 3, 28, 36. The dynamic change in the switches shows that the number of switching operation is 32 for 24 h.

Conclusion

In this paper, a new approach to the dynamic reconfiguration of the power distribution system as a function of the maximum available power was presented. At each period of the day, an optimal network topology is proposed to minimize the losses of active power and the voltage deviation at the level of the nodes while minimizing the reactive power losses. The system average interruption frequency index (SAIFI) and the system average duration index (SAIDI) were used to check the reliability of the optimal configurations obtained. The algorithm proposed using the MIP (Mixed Integer Programming) solver is tested on standard IEEE 15, 33 and 69 node systems. The results obtained show that the algorithm is very efficient and takes into account certain difficulties in the supply of electrical energy because it may happen at a given moment that the available energy is insufficient. These results also show that the optimal topologies found are reliable. This method is a tremendous support for development and makes it possible to satisfy consumers. It highlights the concept of priority consumers who must always supplied.

Abbreviations

MIP: Mixed integer programming; MINLP: Mixed integer nonlinear programming.

Acknowledgements

Not applicable

Authors' contributions

We hereby declare that all the authors (PRN, ATB and SN E) contributed to the design and implementation of the research, the manuscript has been read and approved by all named authors, and there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. All authors read and approved the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Availability of data and material

We confirm that all data generated or analysed during this study are included in the submitted manuscript. All authors confirm that all relevant data are included in the. Moreover, the data that support the findings of this study are available from the corresponding author upon reasonable request. No additional data archiving is necessary.

Declarations

Competing interests
The authors declare that they have no competing interest.

Received: 28 December 2020 Accepted: 26 October 2021
Published online: 17 November 2021

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