International Journal of Engineering

Journal Homepage: www.ije.ir

Market-based Real Time Congestion Management in a Smart Grid Considering Reconfiguration and Switching Cost

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PAPER INFO

Paper history:
Received 21 September 2022
Received in revised form 18 December 2022
Accepted 22 February 2023

Keywords:
Microgrid
Smart Grid
Real-Time Congestion Management
Generation Rescheduling
Soccer League Algorithm

ABSTRACT

Network Real-Time Congestion (RTC) is a bottleneck that limits energy transfer from the generation units or up-grid to the loads. Some factors, such as intermittent generation of renewable resources and forced outages of generating units and load forecasting errors, can lead to Real-Time Congestion Management (RTCM) in a smart grid network. RTCM is a set of methods to eliminate congestion in real-time. To implement RTCM, some approaches can be employed, including network reconfiguration by Remote Control Switches (RCS), load shedding generation and up-grid power rescheduling. In this paper, a two-stage programming model is proposed to find the optimal solution for RTCM using the integration of reconfiguration and market-based approaches. Therefore, following the occurrence of congestion, at the first stage, microgrid central controller (MGCC) or central energy manager implements reconfiguration as the lowest-cost approach to mitigating RTC. The Soccer League (SL) algorithm is employed at the first stage to find the optimal network topology. Subsequently, based on the results obtained from the first stage, a programming model is applied at the second stage to completely eliminate the RTC. The proposed model minimizes a weighted objective function that includes the generation and up-grid rescheduling cost, load shedding cost, switching cost, and congestion clearing time. In order to model switching costs, a new index is defined to prevent risky switching and the depreciation caused by frequent switching. This index is determined based on the critical locations in the network and the age of RCSs. The numerical results demonstrate the efficacy of the proposed model.

***doi:** 10.5829/ije.2023.36.05b.02*

NOMENCLATURE

$Bid_{g,t}^{Real-time}$	Bid of the gth generator at time t	$Bid_{L,t}^{Rael-time}$	Bid of the Lth load at time t
$F_t^{penalty}$	The product of $f_{l,t}^{penalty}$	$\pi_{p,t}$	Cost of the pth switch action at time t
N_L^{Resch}	Number of the participated loads in CM	$\boldsymbol{SeP_l^{WM}}$	Line active power flow sensitivity with respect to the up-grid active power
N_g^{Resch}	Number of the participated generators in CM.	$\boldsymbol{SeP_l^{L}}$	Line active power flow sensitivity with respect to active power load
$N_{p,max}^{sw}$	Maximum allowable number of switching actions for RCS p per day.	$\boldsymbol{w_t}$	Congestion clearing time weighting factor
P_{WM}^0	Initial value of active power flow of the wholesale market	Q_g^0	Initial value of reactive power flow of the gth generator
Q_{WM}^0	Initial value of reactive power flow of the wholesale market	P_{WM}^{max}	Maximum allowable active power purchased from wholesale market
$\boldsymbol{E_p^{dis}}.\boldsymbol{E_p^{age}}$	Distance index, age index	P_g^0	Initial value of active power flow of the gth generator
$\boldsymbol{E_p^{sw}}$	Switching index	$\boldsymbol{s_{p,t}}$	Status of RCS p at time t (1: when the related RCS is opened, and 0: otherwise).
$\boldsymbol{F_l^{max}}$	Maximum apparent flow of the lth line (MVA).	$\boldsymbol{f_{l,t}^{penalty}}$	Thermal rate penalty function of the lth line at time t
$\boldsymbol{I_{E,t}^{max}}$	Emergency-tern thermal rate	$\boldsymbol{t_{clear}}$	Congestion clearing time
$\boldsymbol{I_{L,t}^{max}}$	Long-tern thermal rate	$\boldsymbol{C_L(\Delta P_L)}$	Cost of change in active power of the Lth load
$\boldsymbol{I_{s,t}^{max}}$	Short-tern thermal rate	$\boldsymbol{C_g(\Delta P_g)}$	Cost of change in active power of the gth generator

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Please cite this article as: I. Ehsani, M. Amirahmadi, M. Tolou-Askari, V. Ghods, Market-based Real Time Congestion Management in a Smart Grid Considering Reconfiguration and Switching Cost, ***International Journal of Engineering, Transactions B: Applications***, Vol. 36, No. 05, (2023) 842-857

N_l	Number of branches	$C_{WM}(\Delta P_{WM})$	Cost of change in purchased active power from the wholesale market
N_p	Number of RCSs	SeQ_l^L	Line reactive power flow sensitivity with respect to reactive power load
P_L^{max}	Maximum allowed active power consumed by the *L*th load (MW).	SeQ_l^{WM}	Line reactive power flow sensitivity with respect to the up-grid reactive power
P_L^{min}	Minimum allowed active power consumed by the *L*th load (MW).	Q_l	Reactive power flow of the *l*th line (kVar).
P_{WM}^{min}	Minimum allowable active power purchased from wholesale market	P_l	Active power flow of the *l*th line(kW).
P_g^{max}	Maximum allowed active power generation of the *g*th generator (MW).	ΔP_l	Variation in active power flow in the *l*th line (kW)
P_g^{min}	Minimum allowed active power generation of the *g*th generator (kW).	t_{recon}	Reconfiguration Times
Q_{WM}^{max}	Maximum allowable reactive power purchased from wholesale market	t_{est}	Estimated time to solve reconfiguration equation
Q_{WM}^{min}	Minimum allowable reactive power purchased from the wholesale market	Q_l^0	Initial value of reactive power flow of the *l*th line (kVar).
Q_g^{max}	Maximum allowed reactive power generation of the *g*th generator (kVar).	P_l^0	Initial value of active power flow of the *l*th line(kW)
Q_g^{min}	Minimum allowed reactive power generation of the *g*th generator (kVar).	$t_{clear,Resch}$	Rescheduling Time
R_g^{Down}	Ramp down rate of the *g*th generator (kW/h).	ΔQ_l	Variation in reactive power flow in the *l*th line (kVar)
R_g^{up}	Ramp up rate of the *g*th generator (kW/h).	t_{clear}^{max}	Maximum allowed time for congestion clearing time
$t_{clear,E}^{max}$	Maximum Emergency-tern clearing time	$s_{p,t,recon}$	Status of RCS *p*th at time t after reconfiguration
$t_{clear,L}^{max}$	Maximum Long-tern clearing time	w_k	Switch action weighting factor
$t_{clear,s}^{max}$	Maximum Short-tern clearing time	w_f	Thermal-Rate weighting factor
D	Set of scenarios that guarantee the radial topology of the network	w_c	Congestion management cost weighting factor.
L	Index of load	SeP_l^g	Line active power flow sensitivity with respect to the generator active power
g	Index of DGs	ΔP_L	Change in the active power of the *L*th load (kW).
k	Number of scenarios that guarantee the radial topology of the network	ΔQ_L	Change in reactive power of the *L*th load (kVar).
l	Index of branches	SeQ_l^g	Line reactive power flow sensitivity with respect to generator reactive power
m	Index of PVs	ΔQ_g	Change in reactive power of the *g*th generator (kVar).
n	Index of WTs	ΔQ_{WM}	Change in reactive power of up-grid (kVar).
p	Index of switch	ΔP_{WM}	Change in the active power of up-grid (kW).
t	Index of hour	$P_{L,t}$	Total power demand *L*th load at time *t* (kW)
ΔP_g	Change in active power of the *g*th generator (kW).		

1. INTRODUCTION

Microgrid congestion is a bottleneck that limits energy transferring from the generation units or up-grid to the loads. It occurs when the transmission line cannot be operated in a specific configuration of generation and consumption [1, 2]. More attention on renewable units and increasing connections between them for supplying power raise the probability of congestion resulting from forecasting errors [3]. Therefore, it is necessary to use an efficient method for solving this problem [4]. Generally, there are two main procedures for Congestion Management (CM), the first being the pre-real time by system operator almost performed by motivational methods. Wu and Oren [5], O'Connell et al. [6] and Verzijlbergh et al. [7] proposed the dynamic tariff method. Huang and Wu [8] suggested the dynamic subside method by modifying the drawbacks of the dynamic tariff method. Andersen et al. [9], Hu et al. [10] proposed the capacity market, and Zhang et al. [11] have proposed the ancillary services market to solve the pre-real time congestion problem. All the mentioned proposals are based on giving financial incentives to consumers for shifting their consumption to other less congested hours [12]. In fact, these methods determine rewards to flexible demand for shifting their consumption to confront probable congestion [13]. The second process of CM is called RTCM which includes methods to remove the congestion-inducing RT by forecasting error, contingences and cascading failure. The proposed methods are based on motivation and reconfiguration. Biegel et al. [3], Huang and Wu [3, 14] suggested the motivation method by making a real-time market that acts based on flexible load shifts. Another research proposed a reconfiguration method and reactive power control method for RTCM [15]. Viawan and Karlsson [16], Ramesh and Ranjith Babu [17] reported that congestion is managed by reactive power control such as the operation of transformer taps, Flexible Alternating Current Transmission System

(FACTS) devices, or phase shifters. Generally, in research that has used the reactive power control methods for RTCM, voltage constraints take precedence over thermal constraints, as a voltage problem is more critical than a thermal problem while ignoring thermal problems can cause irreparable damage to the system. Another method for RTCM is through network reconfiguration [18]. Huang et al. [19] provided a prioritization based on congestion management costs, and according to this prioritization, free (or almost free) reconfiguration methods are preferred to CM because of lower defined DR cost and development investment.

Microgrid networks are designed in the form of a ring to have appropriate reliability but are operated in the form of a radius to maintain the voltage and balance of the system [20]. With the advancement in technology and communication and power system monitoring in smart distribution networks, the option of using RCSs to reduce the cost of losses was proposed. In this respect, several investigators [21-27] have tried to solve this optimization problem by different methods. Some studies have proposed genetic algorithms to solve this problem. Later, researchers thought of using RCSs to solve the congestion problem [28], but optimization for this purpose is an integer nonlinear optimization problem that is generally hard to solve. There are many methods to solve this problem; for instance, Franco et al. [29] recommended Mix Integer Linear Programing (MILP), Abur [30] suggested Linear Programing (LP), Baran and Wu [31] focussed on forward None Linear Programing (NLP) that has started from one executable point and moved to the next point, which has reduced the cost function more than the previous one (by changing only one pair of switches). Notably, in these methods, the global minimum points may not be found. Enacheanu et al. [32] suggested Genetic Algorithm (GA) to solve this optimization problem by the nonlinear integer latency problem and the tendency to reach a general minimum. However, due to the nature of these methods, there is no guarantee to determine the overall optimal point [33].

To summarize the reviewed studies, the following research gaps can be classified:

• A few studies have analyzed the congestion problem for transmission networks, while there are some differences between congestion problems in distribution networks and transmission networks. One difference is that, unlike the distribution network, transmission systems aren't operated radially. The other difference is that –considering deregulation in the power system –in transmission network, the congestion management is considered an economical issue while in the distribution network, it is regarded as a technical problem. Moreover, generally, RTCM is considered in the N−1 security level in a transmission network. However, in distribution systems, it is commonly not required to take this level of security into account. However, solving the congestion problem for the distribution network seems to be a greater challenge.

•Some studies have tried to solve the congestion problem pre-real time, while the congestion problem in a real-time is a greater challenge for distribution system operators.

•Some papers have proposed RTCM based on the network reconfiguration model, but the main problem in all of these methods proposed is that they may not solve the congestion problem due to poor network infrastructure or compression congestion.

•Another drawback of the literature review on the reconfiguration method is the lack of due attention to this subject. In this regard, some RCSs are located in critical branches of the microgrid system and changing their status in short-term scheduling will cause intolerable disturbances or significant loss of power which are not desirable for MGO.

•Some papers have proposed RTCM based on the market-based model, which is an expensive solution.

• There is an evident lack of a suitable model in most studies to optimize important objective functions simultaneously.

Table 1 provides a comparison of contributions offered by the proposed model with models studied in the literature.

In this paper, a 2-stage optimization problem is defined to reduce microgrid costs while solving congestion problems. The output is the RCSs situation, rate of load shedding for each curtailable load, rate of generation rescheduling, the range changes of the purchase from the wholesale market, and finally reaching the optimal point. To achieve this purpose, congestion is divided into three types, each solved based on the predicted scenarios. The solution to this problem is based on the integration of a reconfiguration method with load shedding, generation rescheduling and purchased changes. The integration of these two independent methods can solve a wide range of congestion problems with any intensity and under any type of network infrastructure to ultimately reach an

TABLE 1. Comparison between the proposed model and similar researches

Ref.	Distribution	Real-Time	Market-base	Reconfiguration	Switch cost
[5-12]	✓		✓		
[3, 14]	✓	✓	✓		
[15-17]	✓	✓			
[28-32]	✓	✓		✓	
[34]		✓	✓		
Proposed method	✓	✓	✓	✓	✓

optimal point in the optimization problem. Importantly, unlike previous methods, in this method, all possible scenarios are inspected and the most optimal solution is selected. Moreover, a new switching index based on the critical locations in the network and switch ages is defined to assign allowable RCS actions for each.

Given the previous analysis, the main contributions of this paper are as follows:

1) Integrating the reconfiguration method with the market-based method to solve the congestion problem.
2) Minimizing the elimination cost of RTC in a microgrid using a new approach
3) Proposing a new index for switching action based on switch ages and critical locations to maintain the reliability of the RCS switching procedure.

The rest of this paper is organized as follows: Section 2 deals with the problem and problem formulation; in section 3 the proposed algorithm is discussed; numerical results and discussions on a test system are dealt with in section 4; and finally in section 5, conclusions are presented.

2. MODELLING

2. 1. Problem Discussion

In this paper, the congestion problem is solved in real time and the corrections are performed in real time, too. RTCM is proposed because we have a day-ahead planning and a series of forecasting errors is likely to occur in this planning, which causes real-time congestion. For this purpose, we assume that based on load forecasting and switch index, the amount of generation scheduling, consumption scheduling, purchasing from the wholesale market, and situation of RCSs considering switch constraints are determined for the next 24 hours in a day-ahead manner. In the next step based on literature [35], the thermal rate is obtained which is a defined amount of current that flows in the line and induces the maximum allowed temperature in the conductor. Also, based on its intensity, it is divided into three categories: short-term, long-term and emergency time, considering the thermal rate in the three mentioned categories. Then, the real-time load, generation and switch situation are considered based on real data. Afterward, the system is managed based on a 2-stage optimization problem when faced with congestion caused by overload, generator outages, and changes in weather conditions in real time. Loads and generation variations during the RTCM process are taken into account by classifying the clearing time into subsequent subintervals. The proposed RTCM in this paper is performed in two stages. The first stage is network reconfiguration based on minimizing the load of the congested line which is solved by the Soccer league algorithm considering minimizing switch cost. In the second stage, an optimization problem is proposed to plan the changing of the pattern of generation, consumption and purchase from the wholesale market to minimize the cost of RTCM based on the generator bid strategy, power price in the wholesale market, and load shedding cost at cleaning time. This problem is solved by defining the sensitivity coefficient of each line for a change in the generation of each generator, load of each consumption, and purchase from the wholesale market. In this model, the cleaning time is obtained by thermal rates and the problem solution is solved according to the cleaning time and the generators as well as the ramp rate and down rate of loads.

2. 2. Problem Formulation

In this section, a 2-stage optimization problem is proposed in accordance with the switching cost for the RTCM based on the network reconfiguration in the first step. Also, in the second step, it is proposed for changing the pattern of generation, consumption, and purchase from the wholesale market. The purpose of this optimization problem is to solve the real-time congestion problem in the shortest time and by the lowest possible cost. At all times, the conductor currents in all microgrid lines must be lower than the thermal rates obtained by the multi-level method to determine the allowable current of the lines in the short-, long- and emergency term. Otherwise, the proposed model in this paper solves real-time congestion, depending on the type of congestion, before the end of clearing time. Therefore, in times of potential congestion (short-term, long-term or emergency) according to the penalty coefficient, the main priority minimizes additional current on the congested lines by reconfiguration and, if necessary, by changing the pattern of generation, consumption and purchase from the wholesale market. Thus, if the current of the lines of the microgrid is less than the long-term thermal rate, the thermal limits are not violated because the lowest thermal rate is the long-term thermal rate.

$$I_{l,t} \leq I_{L,t}^{max} \rightarrow safe\ mod \tag{1}$$

Otherwise, there are three cases where RTCM must be performed in each case according to the clearing time.

Emergency time congestion:

$$I_{l,t} \geq I_{E,t}^{max} \quad \rightarrow t_{clear} \leq t_{clear,E}^{max} = 5min \tag{2}$$

Short time congestion:

$$I_{s,t}^{max} \leq I_{l,t} < I_{E,t}^{max} \rightarrow \ t_{clear} \leq t_{clear,s}^{max} = 15min \tag{3}$$

Long time congestion:

$$I_{L,t}^{max} \leq I_{l,t} < I_{s,t}^{max} \rightarrow \ t_{clear} \leq t_{clear,l}^{max} = 2h \tag{4}$$

If any congestion is detected, the type is first determined, and then the clearance time is determined accordingly. This time is mentioned as the conductor tolerance threshold for this overcurrent in the congested line. Therefore, before reaching this threshold, the congested line can withstand this overcurrent. Often for long-term congestion, without any action, the congestion problem is solved due to the passage of the peak time or the elimination of events without any action for network reconfiguration or changing the pattern of generation, consumption and purchase. So, basically, the occurrence of this type of congestion is not a difficult problem for microgrids. In this paper, the principle is to solve short-term and emergency-term congestion. Emergency and short-term congestions are managed by a two-stage optimization problem. This problem is solved through the soccer league algorithm to minimize overcurrent in the congested line by network reconfiguration in the first stage and determining the amount of change in generation, consumption and purchase pattern as decision variables in the second stage for minimizing the cost of RTCM.

2. 2. 1. The First Stage of RTCM Microgrids are designed in the form of a ring to enhance reliability but by putting RCSs, there are operated in the form of a radius. On the other hand, RCSs are used to improve system parameters such as power balancing and voltage profile [22]. The configuration of a microgrid should remain radial after the reconfiguration of operations. Thus, the main constraint in the use of RCSs is maintaining the radial structure of the network; to do so, the states of RCSs are arranged in a way that ultimately leads to maintaining the radial structure of the network. In this respect, first, all the different states of open or closed RCSs are examined. Then, based on the graph theory, all the scenarios that lead to the preservation of the radial structure of the network are collected in a set. Also, scenarios outside this set are not used in the algorithm, so a group of configuration scenarios that have a radial structure is collected in the following set, and scenarios outside this set are not used in the algorithm.

$$D = \{D(1), D(2), \ldots\ldots, D(k)\} \tag{5}$$

The thermal rate penalty function helps to select scenarios in which there are no congested lines in the network as the optimal scenario. In addition, as far as possible, scenarios with the lowest penalty coefficient should be determined. The amount of penalty coefficient for the thermal rate of lines, depending on types of congestion, is shown in Figure 1.

$$F_t^{penalty} = \prod_{l=1}^{N_l} f_{l,t}^{penalty} \tag{6}$$

After detecting a short-term or emergency-term congestion, the algorithm should change the status of RCSs to reduce the currents of the congested lines in such a way that, ideally, not only is the congestion eliminated ($F_t^{penalty}$=1) but also the winning scenario

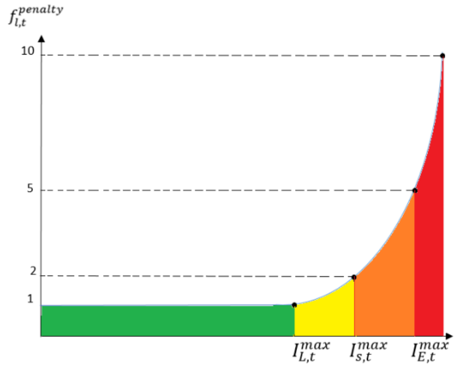

Figure 1. Amount of penalty coefficient for the thermal rate of lines

has the least RCSs change compared to the planned scenario for the desired time.

$$OF = Min\left[w_f\left(\prod_{l=1}^{N_l} f_{penalty,T}^{l}\right) + w_k\left(\sum_{p=1}^{N_p} \pi_{p,t}\left|N_{p,t}^{sw}\right|\right)\right] \quad \forall D(k) \in \{D\} \tag{7}$$

$$N_{p,t}^{sw} = s_{p,t} - s_{p,t-1} \tag{8}$$

Some of the RCSs are located in critical branches of the microgrid system and changing their status in short-term scheduling will cause intolerable disturbances or significant loss of power which are not desirable for MGO. Another scenario that prevents short-term reconfiguration is the RCS ages according to asset management monitoring data. To address these issues, a new index for switching action of each RCS is defined as follows:

$$E_p^{sw} = E_p^{dis}.E_p^{age} \tag{9}$$

$$E_p^{dis} = \begin{cases} 0 & Distance < a \\ \frac{distance-a}{b-a} & a \le dis \le b \\ 1 & Distance > b \end{cases} \tag{10}$$

$$E_p^{age} = \begin{cases} 1 & age < c \\ \frac{d-Age}{d-c} & c \le Age \le d \\ 0 & Age > d \end{cases} \tag{11}$$

$$N_{p,max}^{sw} = \lfloor E_{p,max}^{sw} N_{max} \rfloor \tag{12}$$

$N_{p,max}^{sw}$ is an integer value. N_{max} can be calculated by the expected lifetime of RCSs and the maximum number of switching in the lifetime. Considering an expected lifetime of 30 years for each RCS [36, 37], the possible maximum switching actions are computed as 12 times per day where ten operations are assumed for reconfiguration and two operations are devoted to fault detection, isolation and maintenance duties. The number of switching actions per day must be limited as follows:

$$N_{p,day}^{sw} \le N_{p,max}^{sw} \tag{13}$$

In this paper, according to the current generation, consumption and purchased scheduling, the scenario which has the lowest amount of thermal rate penalty function and the least change of RCSs, compared to the initial situation, is selected as the winning scenario (ideally, by changing a pair of switches, the thermal rate penalty function equals one). The difficulty of solving this optimization problem is to reach the global optimal solution. Therefore, the use of an algorithm with high-performance speed and accuracy and appropriate structure to solve this optimization problem seems necessary. For this purpose, the soccer league algorithm is proposed. The theory of this algorithm is comprehensively demonstrated by Moosavian and Roodsari [38]. In this section, while briefly explaining the rules of the algorithm, based on the existing conditions in this optimization problem, adaptation is carried out. The rules of this algorithm are based on soccer leagues and the principles of competition between teams (scenarios). Thus, the champion team of the league is selected as the preferred scenario. In this algorithm, each team participates in a k-1 match and (k * (k-1))/ 2 matches are held in one season, where *k* is the number of scenarios that maintained the radial structure of the microgrid. The teams get closer to the top of the league table with each win, but their position in the league table goes lower with each loss. There is a competition at the bottom of the league table at the end of the season. Here, the two last teams in the league are relegated (Falling points), and the two top teams in the second division (promotion points) will replace the relegated teams from the first division. In this special optimization problem, the second division league is designed to increase the speed of convergence so that weaker teams (scenarios) for different hours compete in parallel with the stronger teams (scenarios) in the first division league. The final position of each team is determined at the end of the competition based on their total score. Competition between teams is used to win the league championship, and internal competition of players is used to progress to converge to the global optimal point (to increase the speed of performance) which is mentioned in the algorithm by Imitation and Provocation.

One advantage of soccer league algorithm is using a combination of coarse and fine scale search processes. There is a rather similar process in the particle swarm optimization (PSO), but the soccer league algorithm uses different operators for evaluating the search space. On the other hand, PSO applies only one population while the soccer league uses several populations or teams in the searching process. In addition, the soccer league takes into account the best player of the league or superstar player (SSP), while all players should imitate him.

Based on the proposed method in this step, the scenario with the lowest amount of penalty function and the least change in the RCSs state, compared to the planned configuration, is selected as the reconfiguration scenario. In most cases, only by the reconfiguration method proposed in this step is the congestion problem managed, and this problem is completely solved ($F_t^{penalty}$=1). However, sometimes due to poor network infrastructure or intensity of congestion, free methods (reconfiguration) alone cannot solve real-time congestion problems in the microgrid. Therefore, it is necessary to integrate this method with market-based methods to have a principled RTCM. Under these conditions, first, the network configuration is changed based on the reduction of congested lines current and the winning scenario replaces the planned scenario. Then, if the congestion problem is not solved, the proposed method in the second step is employed to generate rescheduling, load shedding, and changing the pattern of purchase from the wholesale market to solve real-time congestion problems.

2. 2. 2. The Second Stage of RTCM In the second step, the line active and reactive power flow sensitivity for the generator, load and purchased active and reactive power, is initially calculated. Then, an optimization problem is proposed to solve the congestion problem in real time based on reducing the costs of RTCM by an optimal change in the pattern of generation, consumption and purchase from the wholesale market, as elaborated in this section. In this optimization problem, the congestion clearing time is determined according to the type of congestion, and the variation of the reactive power in the congested lines is considered. Furthermore, the downtime of Curtailable load and the ramp-down and ramp-up rates of the generating is taken into the RTCM problem. Therefore, in this proposed model, the operation conditions are considered more realistic than in other models. In addition, the multi-level thermal rate increases reliability and makes RTCM process more economical.

$$SeP_l^g = \frac{\Delta P_l}{\Delta P_g} \quad l = 1,2,\dots,N_l \quad g = 1,2,\dots,N_g^{Resch} \tag{14}$$

$$SeQ_l^g = \frac{\Delta Q_l}{\Delta Q_g} \quad l = 1,2,\dots,N_l \quad g = 1,2,\dots,N_g^{Resch} \tag{15}$$

$$SeP_l^L = \frac{\Delta P_l}{\Delta P_L} \quad l = 1,2,\dots,N_l \quad L = 1,2,\dots,N_L^{Resch} \tag{16}$$

$$SeQ_l^L = \frac{\Delta Q_l}{\Delta Q_L} \quad l = 1,2,\dots,N_l \quad L = 1,2,\dots,N_L^{Resch} \tag{17}$$

$$SeP_l^{WM} = \frac{\Delta P_l}{\Delta P_{WM}} \quad l = 1,2,\dots,N_l \tag{18}$$

$$SeQ_l^{WM} = \frac{\Delta Q_l}{\Delta Q_{WM}} \quad l = 1,2,\dots,N_l \tag{19}$$

These sensitivity factors are calculated in real time before beginning the optimization process, by Equations (14-19) with the proposed method by Esfahani and Yousefi [34], immediately after the occurrence of congestion and by the full Newton–Raphson method. Therefore, during the optimization process, power flow solutions are not required, which accelerated the solution of RTCM. The calculation method for obtaining these factors is based on power flow equations neglecting $Q - \vartheta$ and $P - V$ coupling as described by Dutta and Singh [39].

Hence, the second step of RTCM can be formulated as follows:

$$min\left\{w_c\left(\sum_{g=1}^{N_g^{Resch}} C_g\left(\Delta P_g\right)+\sum_{L=1}^{N_L^{Resch}} C_L(\Delta P_L)+C_{WM}(\Delta P_{WM})\right)\right)+w_t.t_{clear,Resch}\right\} \quad (20)$$

This optimization problem is performed aimed at minimizing the RTCM costs and the congestion clearing time by considering generation rescheduling cost, load shedding cost, and cost of change in the purchased pattern.

Although minimizing the RTCM costs is the main goal of this problem, in emergency congestion occurrence, quick solution of this problem might be required. Thus, congestion-clearing time is added to the objective function of this optimization problem. Here, w_t and w_c are the weight factors which have different values depending on the intensity of congestion, and t_{clear}^{max} is defined as the maximum allowed time for congestion clearing time determined according to the worst condition of congested lines as formulated in Equations (22) and (23).

$$w_t = 20 \max f_{l,t}^{penalty} \quad l = 1,2,\dots,N_l \quad (21)$$

$$t_c = \begin{cases} t_{clear,s}^{max} & if: \quad I_{s,t}^{max} \le I_{l,t} < I_{E,t}^{max} \\ t_{clear,E}^{max} & if: \quad I_{l,t} \ge I_{E,t}^{max} \end{cases} \quad \forall\, l \in congestion\ line \quad (22)$$

$$t_{clear}^{max} = \min t_c \quad (23)$$

The constraints of this optimization problem are formulated as follows:

$$t_{clear,Resch} \le t_{clear}^{max} - t_{recon} - t_{est} \quad (24)$$

$$P_l^2 + Q_l^2 \le (F_l^{max})^2 \quad (25)$$

$$(P_g^{min} - P_g^0) \le \Delta P_g \le (P_g^{max} - P_g^0) \quad (26)$$

$$(Q_g^{min} - Q_g^0) \le \Delta Q_g \le (Q_g^{max} - Q_g^0) \quad (27)$$

$$(10 \times R_g^{Down}.t_{clear}^{max}) \le \Delta P_g \le (10 \times R_g^{Down}.t_{clear}^{max}) \quad (28)$$

$$(P_{WM}^{min} - P_{WM}^0) \le \Delta P_{WM} \le (P_{WM}^{max} - P_{WM}^0) \quad (29)$$

$$(Q_{WM}^{min} - Q_{WM}^0) \le \Delta Q_{WM} \le (Q_{WM}^{max} - Q_{WM}^0) \quad (30)$$

$$P_L^{min} - P_L^{max} \le \Delta P_L \le 0 \quad (31)$$

$$\sum_{g=1}^{N_g^{Resch}}\left(\Delta P_g\right)+\sum_{L=1}^{N_L^{Resch}}(\Delta P_L)+\Delta P_{WM}=0 \quad (32)$$

Congestion clearing time is limited by Equation (24) in order to achieve a reliable answer. The line flow limit with regards to load shedding, generation rescheduling and changes of purchase from the wholesale market is shown in Equation (25). The allowed changes in generators' active and reactive power are determined by Equations (26) and (27) respectively. However, in Equation (28), acceptable variation in the active power of generators is represented according to t_{clear}^{max} and their ramp rates. Allowed changes of purchased active and reactive power from the wholesale market are determined by Equations (29) and (30), respectively. Load variation constraints are presented in Equation (31). Also, the power balance according to changes in active power at the slack bus is addressed in Equation (32).

The cost of load shedding and generation rescheduling are calculated below:

$$C_g\left(\Delta P_g\right) = Bid_{g,t}^{Real-time} \times \left(\Delta P_{g,t}\right) \quad g = 1,2,\dots,N_g^{Resch} \quad (33)$$

$$C_L(\Delta P_L) = Bid_{L,t}^{Rael-time} \times (\Delta P_{L,t}) \quad L = 1,2,\dots,N_L^{Resch} \quad (34)$$

where:

$$P_l = P_l^0 + \sum_{g=1}^{N_g^{Resch}}\left(\Delta P_g.SeP_l^g\right) + \sum_{L=1}^{N_L^{Resch}}\left(\Delta P_L.SeP_l^L\right) + SeP_l^{WM}.\Delta P_{WM} \quad (35)$$

$$Q_l = Q_l^0 + \sum_{g=1}^{N_g^{Resch}}\left(\Delta Q_g.SeQ_l^g\right) + \sum_{L=1}^{N_L^{Resch}}\left(\Delta Q_L.SeQ_l^L\right) + SeQ_l^{WM}.\Delta Q_{WM} \quad (36)$$

After the convergence of this optimization process, the final generation at the slack bus is achieved by a full AC power flow solution. At this power flow, the generation of each generator (except the slack bus) and the amount of purchase from the wholesale market and load shedding are set to the outcome values obtained from this optimization process.

3. PROPOSED ALGORITHM

The proposed algorithm for real-time congestion management based on reconfiguration (red color) and generation rescheduling, load shedding, changing the pattern of purchase from the wholesale market (blue color) and considering switch action is shown in Figure 2. Since the base of this paper is an RTCM with the lowest cost and considering that rescheduling tools are an expensive method to solve congestion, priority is given to cheaper methods for the RTCM. Therefore, the first stage of RTCM is solving this problem through the reconfiguration method and the second stage includes load shedding, generation rescheduling and changing the pattern of purchase. Congestion clearing time is subdivided into subintervals in order to evaluate the effects of power system variations or load change on the congested line current. In step 4 of this algorithm, the number of switching actions per day is considered. During the RTCM procedure, if the power system variations lead to incrementing the current of the congested line, the commands will be stopped and updated based on solving the congestion problem in the new conditions. Stage 2 of this model is divided into two steps. In the first step, reactive power change is ignored (ΔQ=0). If this problem is solved in the first step, the answer feasibility must be evaluated by power system operation constraints and the power flow solution should be checked (such as the power flow of branches and voltage magnitude of buses). If the answers do not satisfy system constraints or the solver fails to find a reliable solution, reactive power changes must be taken into the formulation to find out a feasible and reliable solution in step 2 ($\Delta Q \neq 0$).

4. NUMERICAL RESULTS

A microgrid test system with four dispatchable DGs, thirty-two buses, one wind unit, one photovoltaic unit and five load points (four load points with adjustable consumption) are considered for studying the performance of the RTCM model. The microgrid, presented by Shirmohammadi and Hong [23] which has thirty-two sectionalizing switches and five tie switches, is shown in Figure 3. A Pentium V, 4-GHz, 6-GB RAM computer is used for real-time congestion management

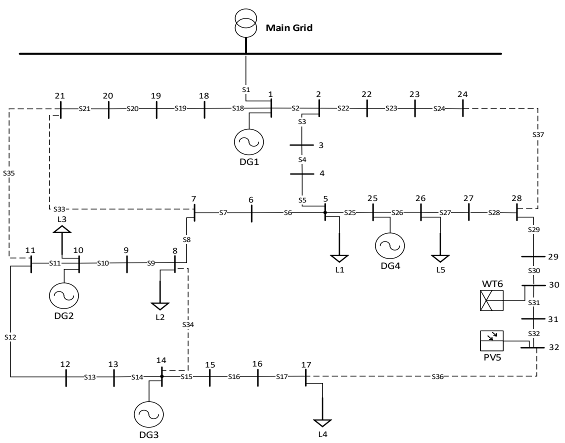

Figure 3. The diagram of the test microgrid

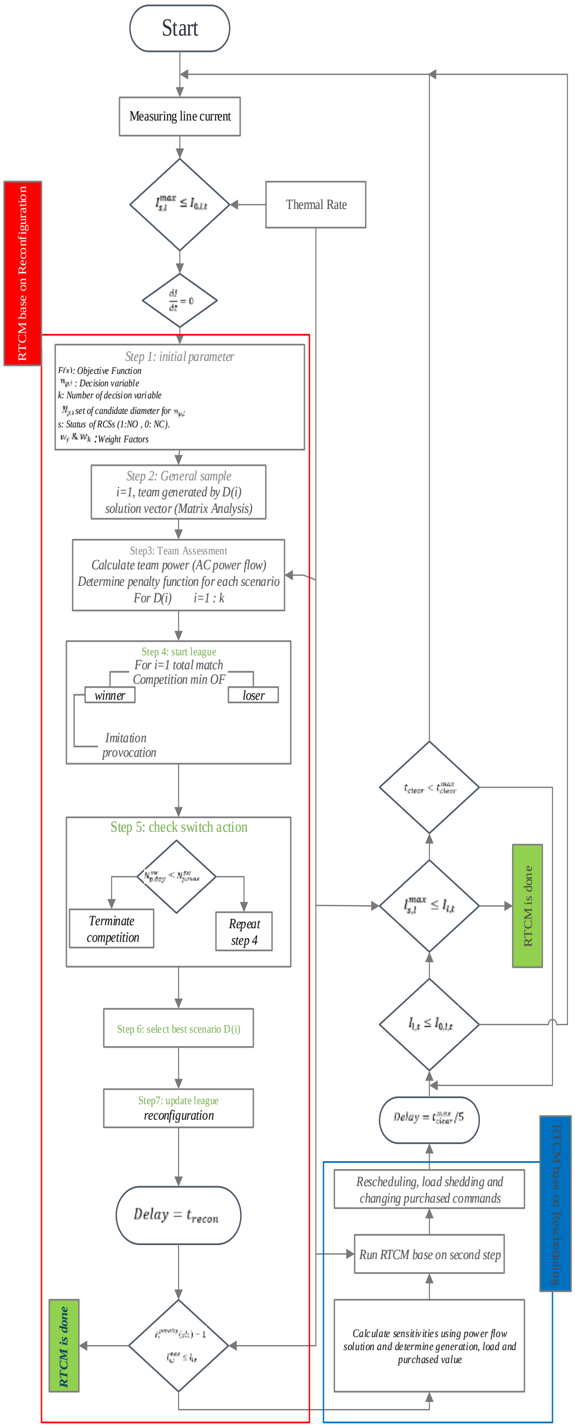

Figure 2. The proposed RTCM algorithm

calculations in this paper. Power flow solution and system modeling are performed using DIgSILENT software.

With regards to the network shown in Figure 3, initially, generation, consumption and purchase rescheduling as well as the situation of RCSs are determined for 24 hours a day (in a day-ahead manner) considering network constraints. In addition, the generation, rescheduling constraint, and load-shedding constraints are specified. Then, the allowable line current for the next one-hour intervals is determined. The proposed algorithm can be used for both considering the switch cost and non-considering the switch cost. In this section, both strategies are used to solve the RTCM problem and show that considering this factor has a notable effect on the RTCM costs in the RTCM problem. Then, the network under this configuration and power flow are examined in real-time and in encountering scenarios that eventually create specific contingencies. These defined scenarios are the result of forecast errors and the faults which lead to generator outages. The scenarios chosen can cause congestion in one or more lines under this certain condition. Afterward, the proposed model in section 3 is applied to managing real-time congestion for these cases and the obtained results are analyzed. The defined cases that lead to congestion are as follows:

Case 1. L2 increase 35% at times 8-9

Case 2. outage of G3 due to a fault occurrence at times. 24-25

These cases are defined as events that happen in real time and lead to real-time congestion in the network, which can be managed by the proposed RTCM in this paper.

As mentioned, initially, generation, consumption and purchase rescheduling as well as the situation of RCSs are determined 24 hours a day. Since displaying these figures for 24 hours a day confuses the reader, this information is only displayed for the cases (and hours) where the scenario occurs. Table 2 shows the switching schedule for each case (D9 and D4 configuration), as well as the maximum allowable and planned switching actions for each RCSs. The characteristic of DGs and the limitation of each unit for each case are displayed in Table 3. Moreover, Table 4 summarizes the characteristics of loads in each case. Also, the line loading limitations are shown in Table 5.

Figure 4 shows the calculated amounts of age index, distance index, and switching index for all RCSs. As can be seen, RCSs with lower values of age index (e.g., RCS 7, 12, 36) or with lower values of distance index (e.g., RCS 6) create lower amounts of switching index. According to Equation (12), the maximum allowable switching actions for each RCSs can be extracted as shown in Table 1.

TABLE 2. Planned configuration for each case

	P **(switch number)**	**Max allowable switch action** $N_{p,max}^{sw}$	**Planned switch action** $N_{p,day}^{sw}$	$s_{p,t}$ **case2 (8-9) D9**	$s_{p,t}$ **case3 (17-18) D4**
Sectionalizing	4	8	4	1	0
	6	3	2	0	0
	7	7	5	0	1
	8	9	6	1	0
	9	5	3	0	0
	10	8	6	0	0
	11	3	0	0	0
	12	9	3	1	0
	13	1	0	0	0
	15	2	0	0	0
	16	9	0	0	0
	17	4	0	0	0
	22	2	0	0	0
	23	1	0	0	0
	24	3	0	0	0
	28	2	0	0	0
	33	6	4	0	0
Tie	34	8	6	0	1
	35	9	5	0	1
	36	6	4	1	1
	37	9	5	1	1

TABLE 3. Characteristics of DGs

	Generation unit	$Bid_g^{day-a-head}(\frac{\$}{kWh})$	$Bid_g^{Real-time}(\frac{\$}{kWh})$	$P_{g,t}(kW)$	$P_g^{max}(kW)$	$R_g^{up}(\frac{kW}{min})$	$R_g^{Down}(\frac{kW}{min})$
Case1 (8-9)	DG1	0.148	0.653	4000	5000	350	-350
	DG2	0.142	-	5000	5000	112	-112
	DG3	0.187	0.793	2500	4000	251	-251
	DG4	0.228	0.859	700	۷900	458	-458
	PV5	-	-	1200	3000	-	-
	WT6	-	-	2100	3500	-	-
	P_{upgrid}	0.128	0.225	0	-	-	-
case3 (22-23)	DG1	0.159	--	5000	5000	350	-350
	DG2	0.164	0.912	4500	5000	112	-112
	DG3	0.198	0.583	3000	4000	251	-251
	DG4	0.238	0.847	600	۷900	458	-458
	PV5	-	-	1000	3000	-	-
	WT6	-	-	2000	3500	-	-
	P_{upgrid}	0.161	0.312	0	-	-	

TABLE 4. Characteristics of loads

	Load	Type	P_{Li}	$Bid_{L,t}^{Real-time}(\frac{\$}{kWh})$	Min-max capacity (Kw)	Down Time (kW/min)
Case1 (8-9)	L1	Curtailable	3000	1.466	0-700	150
	L2	Curtailable	2700	1.129	0-600	125
	L3	Curtailable	3100	0.989	200-600	160
	L4	Curtailable	3500	1.108	100-700	117
	L5	Uncurtailable	3200	-	-	-
Case2 (22-23)	L1	Curtailable	2900	1.927	0-800	150
	L2	Curtailable	3500	1.832	0-800	125
	L3	Curtailable	3200	1.174	200-800	160
	L4	Curtailable	3800	1.437	100-500	117
	L5	Uncurtailable	2700	-	-	-

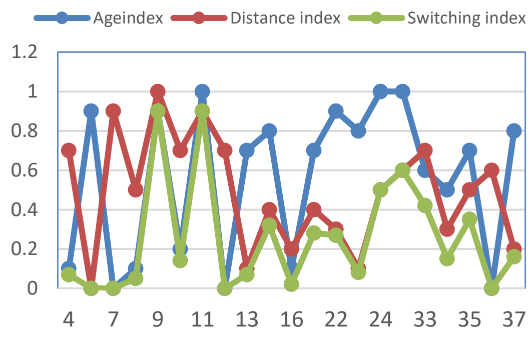

Figure 4. Switching indices for each RCS

In these studies, we assumed that cost function of load shedding and generation rescheduling for RTCM is as Equation (37).

$$cost\ of\ RTCM = \sum_{g=1}^{N_g^{Resch}} (\Delta P_{g,t} \times Bid_{g,t}^{Real-time}) + \sum_{L=1}^{N_L^{Resch}} |\Delta P_{L,t}| \times Bid_{L,t}^{Real-time} + \sum_{p=1}^{N_p} \pi_{p,t} |N_{p,t}^{sw}| \quad (37)$$

4. 1. Obtained Results in Case 1 At times 8-9, the network topology is predetermined as D9 (as depicted in Figure 5 and Table 2). The characteristics of DGs and loads as well as their limitation are displayed in Tables 3 and 4, respectively. The number of switch actions at time t ($N_{p,t,day}^{sw}$) in Table 6 includes the number of planned switch actions in day-ahead in addition to switch actions due to RTCM before 8 o'clock.

Under these conditions, L2 increases by 35% and leads to additional power supplied from the up-grid system at 945kW. In this case, before an increase of L2 in D9 configuration, a power equal to 4000 kW and a current of 200 A flowed in lines 18,19 and 20. Under the new conditions, a power equal to 4945 kW and a current of 247.2 A flow in them. Also, a power equal to 3700 kW and a current of 185A flow in lines 9 and 10. In this respect, a power of 4645 kW and a current equal to 232 A are transmitted through them.

By comparing these currents with the thermal rate (Table 5), we find that these lines are congested. Lines 18, 19 and 20 have emergency congestion and lines 9 and 10 have short-term congestion.

Under these conditions, as shown in Table 8, the solution of the Soccer League algorithm in the first stage of RTCM is network reconfiguration by providing the D37 if we consider the switch cost factor or D19 configuration without considering this factor. Accordingly, the transmission power of the mentioned lines is reduced, and the real-time congestion problem is solved at $F_t^{penalty} = 1$ accordingly. As observed, an RTCM is performed for this case by changing three pairs of switches.

Table 6 compares the configuration of D9, D19 and D37. Figure 5 shows the topological structure of the network in D9, D19 and D37 configurations.

As can be seen, the network configuration in D37 and D19 are similar and the difference lies in the cost of the switch action.

4. 2. Obtained Results in Case 2 At times 22-23, the network topology is predetermined as D4 (as shown in Figure 6 and Table 2). The characteristics of DGs and loads as well as their limitation are displayed in Tables 3 and 4, respectively.

In this case, the outage of G3 due to a fault occurrence leads to additional power supplied from the up-grid system at 3000kW to maintain voltage and frequency and prevent blackouts. In this case, before the outage of G3 in D4 configuration, lines 18, 19, 20, 8 and 33 transmit a power equal to 4000 kW and a current of 200 A. In this connection, a power of 6000 kW and a current equal to 300 A transmit through them. By comparing these currents with the thermal rate (Table 5), we find that these lines are congested. All these lines have an emergency. Under these conditions, the solution of the

TABLE 5. The thermal rate of the line obtained by SR & MR methods

Line	Line Current Rate		
	$I_{L,t}^{max}$	$I_{s,t}^{max}$	$I_{E,t}^{max}$
Lines (1-8)	194	207	237
Lines (9-13)	198	215	252
Lines (14-17)	229	242	270
Lines (18-24)	203	214	245
Lines (25-32)	237	250	278
Lines (33)	194	206	235
Lines (34)	238	251	280
Lines (35)	191	207	240
Lines (36)	195	211	243
Lines (37)	242	254	282

TABLE 6. Switch cost for change, number of switch actions at time *t* and Network configuration in D9, D19 and D37

	***P* (switch number)**	$\pi_{p,t}$ **($)**	$N_{p,t,day}^{sw}$	**D9**	**D19**	**D37**
Sectionalizing	4	2.1	3	1	0	0
	6	1.8	1	0	0	1
	7	3.4	3	0	1	0
	8	2.3	2	1	0	0
	9	1.5	1	0	0	1
	10	4.8	3	0	1	0
	11	6.0	0	0	0	0
	12	3.4	2	1	0	0
	13	7.0	0	0	0	0
	15	5.9	0	0	0	0
	16	4.7	0	0	0	0
	17	6.3	0	0	0	0
	22	7.2	0	0	0	0
	23	4.6	0	0	0	0
	24	3.2	0	0	0	0
	28	3.9	0	0	0	0
Tie	33	3.9	1	0	0	0
	34	2.8	3	0	1	1
	35	7.8	2	0	0	0
	36	4.3	2	1	1	1
	37	6.8	1	1	1	1

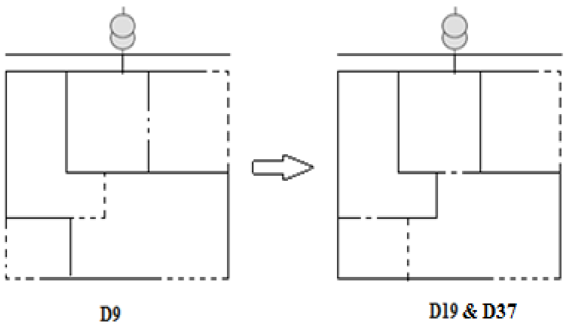

Figure 5. Network structure for D9 & D19 & D37 configuration

Soccer League algorithm is network reconfiguration by providing the D24 with considering the switch cost factor and D46 without considering this factor instead of D4 (as shown in Figure 6). Table 7 compares the configuration of D4, D46 and D24. As a result of this reconfiguration, the amount of $F_t^{penalty}$ penalty has significantly decreased from 43776 to 3672 by considering the switch action factor or 43776 to 3895 by not considering this factor (as shown in Table 8) and the congestion in the mentioned lines has been eliminated. Nevertheless, this reconfiguration causes the congestion of lines 2, 3, 4 and 5 in full RTCM and lines 22, 23, 24, 34, 27, and 28 regardless of the switch action factor. Therefore, to completely solve the congestion problem, the performance of the second stage of RTCM is needed based on the proposed model in this paper. The solution of the second stage determines generation scheduling, load shedding, and changes purchased from the up-grid system. For this case, if the switch cost factor is used in the calculations, the solution is the decrease of 1820 kW purchased from the up-grid system and an increase of 1820 kW in the generation of DG4. The duration of this change is equal to 1820÷458=3.9 min where 458 is the ramp rate of G4 and the cost to $1820 \times 0.847 = \$\ 1541$where 0.847 is G4 real-time bid at time 22-23. In addition, without considering this factor, the cost of this change is $1640 \times 0.847 = \$1388$.

In addition, if the switch action factor is used in the RTCM, there is a 1820kW increase in DG4 generation by the same amount, which will eliminate this congestion and the $153 RTCM cost. Yet, it should be noted that if the switch action factor is ignored, it will lead to irreparable damages to the system according to Table 1. The maximum allowable switch action of switch No. 34 (RCS$N_{p,max}^{sw}$) during the day is equal to 8, while the number of switch actions has reached its maximum value before 22:00 ($N_{p,t,day}^{sw}$ in Table 7), while this switch cannot act at the desired time.

4. 3. Discussion As mentioned, the proposed model in this paper is based on the integration of marketing with the reconfiguration method, for the RTCM in a microgrid. Now, for principled validation, we

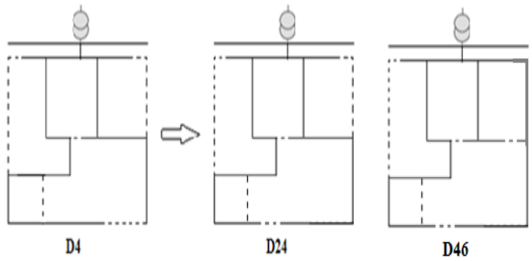

Figure 6. Network structure for D4, D24 and D46 configuration

TABLE 7. Network configuration in D4 and D24

	p **(switch number)**	$\pi_{p,t}$	$N_{p,t,day}^{sw}$	**D4**	**D24**	**D46**
Sectionalizing	4	2.5	4	0	0	0
	6	2.3	2	0	0	0
	7	4.4	4	1	1	1
	8	3.1	2	0	0	0
	9	1.8	1	0	0	0
	10	5.3	4	0	0	0
	11	6.4	0	0	0	0
	12	2.4	3	0	0	0
	13	6.0	0	0	0	0
	15	5.5	0	0	0	0
	16	4.9	1	0	1	1
	17	6.8	0	0	0	0
	22	7.7	1	0	0	0
	23	5.0	0	0	0	0
	24	3.7	0	0	0	0
	28	3.3	0	0	0	1
	33	3.1	4	0	0	0
Tie	34	9.8	8	1	1	0
	35	8.4	3	1	1	1
	36	4.9	5	1	0	0
	37	7.8	3	1	1	1

TABLE 8. RTCM by generation scheduling, load shedding and supplied power from up-grid

			Full RTCM With considering switch cost		**RTCM based on just Rescheduling**		**RTCM based on Reconfiguration and Rescheduling Without considering switch cost**	
/	**Case No.**		**Case1**	**Case 2**	**Case1**	**Case 2**	**Case1**	**Case 2**
	Type of congestion for each line before RTCM	long-term congestion						
		short-term congestion	S9, S10		S9, S10		S9, S10	

	emergency congestion	S18, S19, S20	S8, S18, S19, S20, S33	S18, S19, S20	S8, S18, S19, S20, S33	S18, S19, S20	S8, S18, S19, S20, S33
	Selected configuration	D9	D4	D9	D4	D9	D4
	$F_t^{penalty}$ before reconfiguration	1722	43776	1722	43776	1722	43776
	t_{clear}^{max} (min)	5	5	5	5	5	5
	Select best reconfiguration	D37	D24	_	_	D19	D46
	$F_t^{penalty}$ after Reconfiguration	1	3895	_	_	1	3672
First Stage	$\sum_{k=1}^{n_p} \lvert \Delta s_{p,t} \rvert$	6	2	_	_	6	4
	t_{recon} (min)	1	1	_	_	1	1
	Reconfiguration cost ($)	13.2	7.3	_	_	32.0	20.4
	w_c	_	1	1	1	_	1
	w_t	_	176	122	53	_	169
	ΔP_{G1}	_	0	0	0	_	0
	ΔP_{G2}	_	0	0	+500	_	0
	ΔP_{G3}	_	0	+885	0	_	0
Second Stage	ΔP_{G4}	_	1820	0	0	_	+1640
	ΔP_{upgrid}	_	-1820	-885	-2120	_	-1640
	$\sum_{g=1}^{N_g^{Resch}} (\Delta P_g)$	_	1820	+885	+500	_	+1640
	$\sum_{L=1}^{N_L^{Resch}} \lvert \Delta P_L \rvert$	_	0	0	1620	_	0
	$t_{clear,Resch}$ (min)	_	3.9	3.5	0	_	3.5
	Rescheduling cost ($)	_	1541	701.8	2699	_	1388
Total cost ($)		13.9	1548	701.8	2699	32.0	1408.4
t_{clear} (min)		1	4.9	3.5	5	1	4.5

consider the cases for the above microgrid in a situation where the reconfiguration method or the marketing method is used alone. To implement the method of reconfiguration for RTCM, regarding the red part of Table 8, this method cannot solve the congestion problem alone in all the cases, e.g., case 2.

In column 2 of Table 8, the mentioned cases in this section for RTCM were examined based merely on the market-based model as proposed in this paper (stage 2 of the proposed model in this paper). Finally, in this way, we understand the effect of the integration of marketing methods with the reconfiguration of RTCM. In the first case, if the reconfiguration is not performed, 885 kW of the supplied power from the up-grid system must be reduced and added to Generator G3 to solve the real-time congestion problem. Regarding Equation (35), the cost of congestion management is equal to $701.8. However, if the complete model presented in this paper is employed, this value will reach $13.9. The congestion clearance time also increased to 3.5 minutes due to the ramp-up rate of Generator G3, which was one minute in the integrated model. Calculations are performed similarly for case 2 and the results are generalized. Now, to understand the effectiveness of using the integration model of reconfiguration methods with market-base, it suffices to compare the last two rows and column 2 of Table 8 with the last two rows of Table 8. This comparison eliminates unnecessary costs in the proposed model to solve the real-time congestion problem, and at the same time enhances the effectiveness of this method in the RTCM.

On the other hand, in this paper, a new index for switching action is proposed to prevent risky switching and the depreciation caused by frequent switching. For principled validation, it has been considered that the cases for the above microgrid in a situation where switching action is not considered. The first and third columns of Table 8 show RTCM by the proposed model in this paper, with and without considering the switching cost. In the first case, the network configuration in D37 and D19 are similar and the difference lies in the cost of switch action. As can be seen, the reconfiguration cost is lower when the switching cost is considered. But in the second case, despite taking into account the switching cost, the reconfiguration cost has increased. Yet, it should be noted that if the switch action factor is ignored, it will lead to irreparable damages to the system according to

Table 2, because the number of switch action of switch No. 34 has reached its maximum value and this switch is not able to act at the desired time.

The distinction between considering switch action factor and without considering this factor in RTCM calculations is evident in both cases.

5. CONCLUSION

The high penetration of Distributed Energy Resources (DER) raises new challenges in microgrid operation due to stochastic and intermittent characteristics. This exacerbates the difficulty of congestion management of microgrids in comparison with conventional power systems. On the other hand, with the development of microgrids as well as increased investment for telecommunication infrastructure, distribution networks can be operated online and in real time. In this situation, using the proposed method in this paper can solve a wide range of congestion problems with any intensity and under any type of network infrastructure, and finally reach an optimal point in the optimization problem. This paper proposed real-time congestion management in accordance with the switch cost factor based on integrating a reconfiguration method with the marketing method in the microgrid. The model presented in this paper solves the real-time congestion problem in two steps. In the first step, based on a structural method and switch cost factor, the status of RCSs is determined by the reconfiguration of the microgrid and to reach the global optimal point. This is done to reduce the current in congested lines and thus solve the real-time congestion problem. Then, if the congestion problem is not solved in the first step, a fast, feasible and inexpensive solution is proposed to solve the real-time congestion problem in the next step by considering the ramp-up and ramp-down time of the generators and loads and also determining the sensitivity of each line to these changes. The integration of these two independent methods can solve a wide range of congestion problems with any intensity and under any type of network infrastructure, and finally reach a general optimal point in the optimization problem. Importantly, unlike previous methods, in this method, all possible scenarios are inspected and the most optimal solution is selected. In addition, the division of congestion into long-term, short-term and emergency time and the definition of the congestion clearing time parameter prevent unnecessary costs for RTCM. Numerical results showed that through the method proposed in this paper, the congestion problem in the microgrid is solved at a lower cost and shorter time than other methods. In future work, the energy losses of the distribution lines during congestion management will be studied.

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Persian Abstract

چکیده

در ریزشبکه‌ها از تراکم بعنوان یک محدودیت نام برده می‌شود که مانع از رسیدن انرژی از ژنراتورها به بارها شده و زمانی به‌وجود می‌آید که سیستم نتواند در یک الگوی خاص تولید، مصرف و انتقال بصورت ایمن عمل کند. این درحالی است که تمرکز بیشتر روی واحدهای تجدیدپذیر و مشارکت روزافزون آن‌ها برای تامین توان ریزشبکه‌ها، احتمال وقوع تراکم ناشی از خطای پیش‌بینی را افزایش داده است. لذا با توجه به ضرورت مطلب لزوم استفاده از یک روش کارآمد، برای حل موضوع تراکم زمان واقعی غیر قابل انکار است. استفاده از نقاط مانور شبکه‌های توزیع به همراه تغئیر الگوی تولید مصرف و خرید از بالا دست می‌تواند از آپشن‌های اصلی برطرف کردن تراکم در محدوده زمانی زمان واقعی باشد. در این مقاله یک مساله بهینه‌سازی دو مرحله‌ای بمنظور حل مشکل تراکم زمان واقعی در یک ریزشبکه ارائه شده است. مساله بهینه سازی شامل بازآرایی ساختار توپولوژیک شبکه توسط نقاط مانور در مرحله اول وهمچنین ادغام آن با برنامه های شیفت مصرف و پخش بار بهینه برای کمینه کردن هزینه های میکروگرید در مرحله دوم، در فاصله زمانی مشخص و در نهایت رسیدن به یک نقطه بهینه کلی است. بنابراین پس از وقوع تراکم، نخست تغئیر در پیکربندی شبکه بمنظور کاهش حداکثری میزان تراکم به‌عنوان یک روش ارزان بکار گرفته می‌شود. الگوریتم لیگ فوتبال برای حل این مساله بهینه‌سازی در مرحله اول بمنظور یافتن توپولوژی بهینه شبکه پیشنهاد شده است. سپس بر اساس نتایج بدست آمده از مرحله اول، مدل ارائه شده در مرحله دوم بمنظور رفع کامل تراکم با کمترین هزینه اعمال می‌شود. مدل ارائه شده یک تابع هدف وزنی را کمینه می‌کند که شامل هزینه برنامه ریزی مجدد تولید و خرید از بالادست، هزینه کاهش بار، هزینه سوئیچینگ و زمان پاکسازی تراکم است. در این مقاله بمنظور مدل سازی هزینه‌های سوپیچینگ شاخص جدیدی بر اساس موقعیت مکانی و همچنین طول عمر آن تعریف شده است. مطالعات موردی تاثیر گذاری این روش را در کاهش هزینه ها وحل مساله تراکم نشان می-دهد و این فرصت را برای ریز شبکه‌ها فراهم می‌آورد تا با کمترین هزینه و بدون سرمایه گذاری برای توسعه خطوط و ادوات شبکه و تنها با بازآرایی به همراه کنترل میزان تولید و مصرف و خرید از بالادست در ساعات مشخص، نیازهای شبکه را چه در زمان وقوع تراکم چه در زمان‌های غیر متراکم برآورده کند.