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A New Optimal Distributed Strategy to Mitigate the Phase Imbalance in Smart Grids

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ABSTRACT

In a three-phase distribution system, due to unequal distribution of single-phase loads, load diversities, the different consumption patterns, and growing penetration of renewable energy resources in smart grids, the problem of unbalanced power flow becomes more challenging. In this paper, we propose a new innovative phase imbalance mitigation (PIM) scheme performed by smart meters. With aid of the proposed optimal phase assignment for 3-phase power distribution input feeders known as phase rearrangement (PR), Electrical storages (ES), and the Renewable energy sources (RES), smart meter owners are inspired to assist the distribution system operator (DSO) in diminishing the phase imbalance. This is achieved by employing a proposed connection point assignment system which has the flexibility of selecting the power input among the three phases and management of ESs and RESs. We model this problem into a mixed integer linear program, where smart meter owners minimize their electricity bill. Simulation results confirm the proposed approach and show smart meter owners will save on their electricity bill and the DSO will get benefit by improving the power quality of the grid and significant decrements of the power flow imbalance.

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1. INTRODUCTION

Due to the unequal distribution of single-phase loads, load diversities, and the different consumption patterns, the three-phase distribution system is innately unbalanced [1]. Unequal power distribution among the three phases leads to unfavorable impacts on the power distribution system and its electrical devices. Under these conditions, currents in two of the phases as well as in the neutral line will rise which provoking more energy losses and heating effects as a consequence [2], even causing tripping of the overload-protection circuits of the feeders [3]. The imbalance also lessens the available capacity of transformers and feeders, leading to additional investment costs [4]. Besides, power imbalance will depreciate the power quality, efficiency, and lifetime of the electrical devices. Furthermore, the increasing penetration of distributed renewable energy sources and the intermittency and uncertainty power generation inherent characteristics as well as the arbitrary installation of them among the three phases, the power imbalance problem is becoming more challenging [5], [6]. Consequently, the DSO has to take action to resolve the power imbalance in the distribution grid. A lot of works have been made to answer the PR problem. Conventionally, rephasing procedures in which re-assign loads to phases are generally employed [7]. In [7], optimal rephasing is done by suggesting a mixed-integer optimization of decisions. Besides, in [8], a rephasing method is proposed wherein a particle swarm optimization problem has been solved to diminish the imbalance. The above-mentioned research all have manual operations for rephasing because the required customer service interruption and manual labor will entail significant costs, strategies, and methods that executing them need offline procedures which depend on the previous plans so are not effective for dynamic and hourly load changes. Most of the traditional methods are put in this category [9-11]. One of the well-known and effective strategies for balancing the loads is rearranging

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the connection point of single-phase customers. The feeders' phase of customers is changed somehow that the unequal loading of the grid's phases gets minimized with regards to the balancing requirements [12]. It is commonly done based on the customers' contractual power or the method of counting them additionally the strategy of their average power consumption based on bills' data information. Versus, the online strategies are existed such as converters. They are commonly used for compensating the active and reactive powers. Convertors are online and in the form of hot-line and act based on the component of sequences of the positive, negative, and/or zero for voltage or current parameters. The devices which support these methods are located in the field where a pre-determined node should be getting balanced. They are based on the current injection to nullify the existing neutral current in a way that the sum of these two current vectors will be equal to zero or near-zero [13-15]. These online strategies are optimal or close to optimal but expensive and have high installation and maintenance costs that causes their utilization lesser. From this category, we can suggest the designed device in [16] especially for reducing the imbalance. It introduces a special type of transformer with an innovating winding arrangement and special core structure so that the current of neutral wire would be zero in every side of the transformer.

These mentioned works are lacking to address the dynamic PR challenges. For it, in [17], static transfer switches (STS) have been presented to relocate residential loads from one phase to a different dynamically. Also, none of those has pondered the smart meters' interaction with each other to make the phase re-arranging autonomously.

In future smart grids, the smart meters will be different from existing ones, they will have cloud computing applications and can exchange data and information between the DSO and each other throw the cloud computing environment. In this paper, we present the smart meters which are ready to be online on the internet and can be accessible and programmable by the DSO, and communicable with other smart meters or authorized entities. We explain the PIM problem from the perspective of smart meter owners, where encouragements such as financial incentives are arranged to increase their participation in the DR programs such as the novel idea of this paper. The PIM problem is modeled as a linear program wherein the decision values are the connection points to the three-phase input feeders. Finally, the main contributions of this paper are summarized as follows:

- To avoid the significant challenge of employing the in practice, an extended connection point assignment system is proposed for handling the original PR strategy.
- An efficient algorithm is established to attain the optimal connection point and management of ESs and RESs.
- Benefits to both the DSO and smart meter owners are proven through all-encompassing simulations.
- Preparation of the method does not need any change in electrical structure, devices, or consumers' part except equipping the smart meters with the proposed module.

The remainder of this literature is prepared as follows. Section II presents the system model and formulates the PIM problem as a linear program. In Section III, Developing a distributed algorithm and explaining the procedure of phase assigning are put in it. Numerical results are obtainable in Section IV and Section V includes the conclusions of this paper.

2. SYSTEM MODEL

The distribution grid is the last step in transferring energy to the consumers. Reconfiguring the grid means the change or keep the normal state of open/close keys to increase the parameters of power quality, reliability, and loss reduction. Assume the optimal reconfiguration is done based on the grid loss reduction, the proposed phase assignment of customers is online and leads to reducing the aggregate load imbalance in 3 phase feeders in addition to its important result which is mitigating the neutral current. These mentioned results are the advantages of the proposed method in this paper. Since the consumption pattern of customers is unpredictable, so we cannot achieve the optimal assignment offline even in the condition of relying on the results of clustering. In the following, the proposed strategy, initial implementing requirements, algorithm, and mathematical formulations will be explained. It is worth mentioning that the three-phase customers can be assumed as three single-phase subscribers; but as the three-phase consumers mostly possess three-phase inductive motors, related protective and control circuits, the phase altering without special technical considerations cannot be possible. So, we assume the three-phase customers will not participate in the proposed program, however, the consumption pattern should be considered in the calculation of baseload.

In this paper, the load balancing is carried out in such a way that the exchanged power with the grid on each node is the same value for all three phases. Since customers who possess DGs and storage systems should also be considered in the problem-solving procedure. It is clear that by increasing the rearranging number of customers, the grid would be closer to the balance condition but this operation should be practically and economically limited due to the lifespan of switching devices.

A sample feeder with three phases and one neutral supply the buildings with photovoltaic and energy storage units is shown in Figure 1.

Assume there are a set of smart meter owners who participate in the PR scheme. These smart meters are fed with 3phases. Power flows inside the customers of the same node compared with the grid's main feeders have negligible effects on their voltages. Additionally, electrical lines originating from the same node usually, in normal conditions, have enough capacity to support all the customers. Consequently, for simplicity, the power flow constraints within a node are not considered. However, this proposed PR strategy can be employed when power flow constraints should not be disregarded. Each smart meter is connected to a 3 phase electricity line but gets power from one phase at the same time. The key idea of the proposed PR scheme is to exploit the input phase flexibility among the three phases. To be precise, the DSO offers the customers encouragement to reassign the connected phase, such that power consumptions on each phase are moved to another phase when compared with the other two, which is relatively light-loaded. We assume that each customer equipped with the smart meter also has electrical storage (ES) which needs to hold a predetermined state-of-charge (SOC) between the minimum and maximum boundaries over a time horizon e.g. a day. It has a charger with a specific charging rate and characteristics. Thus, the following constraint must be satisfied:

$$SOC_i\left[t+1\right]=SOC_i\left[t\right]+\left(1-\zeta_i^{ch}\right).E_{t,i}^{ch} -\left(1+\zeta_i^{dch}\right).E_{t,i}^{dch} \tag{1}$$

$$P_{t,i}^{ch}\times P_{t,i}^{dch}=0 \tag{2}$$

where $P_{t,i}^{ch}$ *and* $P_{t,i}^{dch}$ indicate the storage charge power and discharge power of ES i at time instant t, respectively. The charging rates are constrained. Consequently, the feasible values are the solution set of linear inequalities that are finite in number. Also, $E_{t,i}^{ch}$ *and* $E_{t,i}^{dch}$ are the energies of these power in the time horizon [t,t+1]. (1) reflecting the state of charge (SOC) for the ESs and (2) sets the limit that they should not be charged and discharged simultaneously. It is obvious that a portion ζ_{ch} *or* ζ_{dch} of the stored energy due to inefficiency is typically loss; thus the energy effectively stored is $\left(1-\zeta_i^{ch}\right).E_{t,i}^{ch}$, while the released one needed to guarantee a power supply $P_{t,i}^{ch}$ is $\left(1+\zeta_i^{dch}\right).E_{t,i}^{dch}$. The stored energy in ESs should be between the minimum (DOD) and maximum SOC_{max} (3); allowable limits in accordance with the technical specifications that bring about lifetime increase and avoids deep discharging or over-charging events.

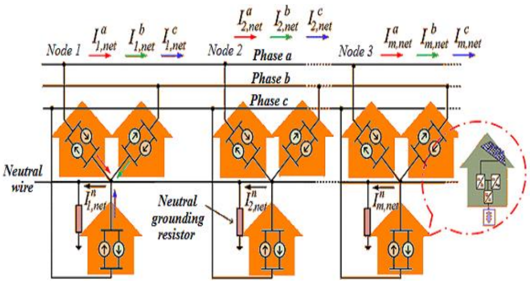

Figure 1. A sample feeder with three-phase and neutral that supply the buildings with photovoltaic DGs and energy storage units

$$\forall t:\ DOD_i \le SOC_i\left(t\right)\le SOC_{i,max} \tag{3}$$

(4) notes the amount of the $SOC\left(end\right)$, stored energy in batteries at the end of the time horizon should be greater than a minimum desirable value $SOC_{desired}$.

$$SOC_{i,desired}\le SOC_i\left(end\right) \tag{4}$$

The generation amount of RESs are considered as negative loads, and vice versa, selling the electricity to the grid as a positive load consumption. However, note that the power balance equation should be met as follow:

$$P_{t,i}^{buy}-P_{t,i}^{sell}+P_{t,i}^{RESs}-P_{t,i}^{ch}+P_{t,i}^{dch}-P_{t,i}^{load}=0 \tag{5}$$

where $P_{t,i}^{buy}$ *and* $P_{t,i}^{sell}$ are the amount of buying/selling electricity of customer i at time instant t. Also, $P_{t,i}^{load}$ is the amount of power consumption and $P_{t,i}^{RESs}$ is the amount of power generation of RESs of customer i.

We express the phase imbalance with the optimization function based on the proposed strategy which at each grid node at time instant t is obtained according to the following constraints and equations.

$$\mathrm{I}_{\mathrm{avg}}^{\mathrm{m,t}}=1/3.\sum\left|\mathrm{I}_{\mathrm{m,net}}^{\mathrm{ph,t}}\right|,\mathrm{ph}\in\left\{\mathrm{a,b,c}\right\} \tag{6}$$

$\mathrm{I}_{\mathrm{avg}}^{\mathrm{m,t}}$ is the average total load of three-phases at node m at a time instant. Consequently, the indices of the original three phases which have imbalance are formulated as below:

$$\mathrm{ph}_{\mathrm{ideal}}^{\mathrm{m,t}}=\min_{\mathrm{ph,ph}\in\left\{\mathrm{a,b,c}\right\}}\left|\mathrm{I}_{\mathrm{m,net}}^{\mathrm{ph,t}}-\mathrm{I}_{\mathrm{avg}}^{\mathrm{m,t}}\right| \tag{7}$$

$$\mathrm{ph}_{\mathrm{incr}}^{\mathrm{m,t}}=\min_{\mathrm{ph,ph}\in\left\{\mathrm{a,b,c}\right\}}\left|\mathrm{I}_{\mathrm{m,net}}^{\mathrm{ph,t}}\right| \tag{8}$$

$$\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}}=\max_{\mathrm{ph,ph}\in\left\{\mathrm{a,b,c}\right\}}\left|\mathrm{I}_{\mathrm{m,net}}^{\mathrm{p,t}}\right| \tag{9}$$

$\mathrm{ph}_{\mathrm{ideal}}^{\mathrm{m,t}}$ is the phase at node m at time instant t which its loads remain untouched. Also, loads of phase $\mathrm{ph}_{\mathrm{incr}}^{\mathrm{m,t}}$ will be increased by assigning smart meter loads on phase $\mathrm{ph}_{shed}^{\mathrm{m,t}}$ to it at node m at time instant t.

$$\mathrm{I}_{\mathrm{ideal}}^{\mathrm{m,t}\ \circ} = \mathrm{I}_{\mathrm{m,net}}^{\mathrm{ph=ph}_{\mathrm{ideal}}^{\mathrm{m,t}}} \ \& \ \mathrm{I}_{\mathrm{shed}}^{\mathrm{m,t}\ \circ} = \mathrm{I}_{\mathrm{m,net}}^{\mathrm{ph=ph}_{\mathrm{shed}}^{\mathrm{m,t}}} \tag{10-11}$$

where $\mathrm{I}_{\mathrm{ideal}}^{\mathrm{m,t}\ \circ}$ is the current of phase $\mathrm{ph}_{\mathrm{ideal}}^{\mathrm{m,t}}$ and $\mathrm{I}_{\mathrm{shed}}^{\mathrm{m,t}\ \circ}$ is the current of phase $\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}}$ both of them at node m at a time instant t which are measured as initial values at the beginning of the optimization time horizon.

To summarize, smart meter i solves the following optimization problem:

$$\begin{aligned} &\min_{\mathrm{x_k} \in \psi_{\mathrm{k}}} (\mathrm{I}_{\mathrm{shed}}^{\mathrm{m,t}\ \circ} - \mathrm{I}_{\mathrm{ideal}}^{\mathrm{m,t}\ \circ} - \sum_{\mathrm{k=1}}^{\mathrm{Ksw}} \mathrm{I}_{\mathrm{k,m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}}} \times \mathrm{sw}_{\mathrm{k,m}}^{\mathrm{incr,t}} + \\ &\sum_{\mathrm{k'=1}}^{\mathrm{Kch}} \mathrm{I}_{\mathrm{k',m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{ch}} - \sum_{\mathrm{k''=1}}^{\mathrm{Kdch}} \mathrm{I}_{\mathrm{k'',m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{dch}} - \sum_{\mathrm{k'''=1}}^{\mathrm{KRESs}} \mathrm{I}_{\mathrm{k''',m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{RES}}) \end{aligned} \tag{12}$$

where $\psi_k = \left\{ \mathrm{sw}_{\mathrm{k,m}}^{\mathrm{incr,t}}, \mathrm{I}_{k',\mathrm{m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{ch}}, \mathrm{I}_{k'',\mathrm{m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{dch}}, \mathrm{I}_{k''',\mathrm{m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{RES}} \right\}$ is the decision value set of the optimization function.

While regarding to the (1-5) for ESs, the below constraints (13) should also be considered for each smart meter:

$$\mathrm{sw}_{\mathrm{k,m}}^{\mathrm{incr}} \ \& \ \mathrm{sw}_{\mathrm{k,m}}^{\mathrm{shed}} \in \{0,1\}; \Sigma \mathrm{sw}_{\mathrm{k,m}}^{\mathrm{incr,t}} + \mathrm{sw}_{\mathrm{k,m}}^{\mathrm{shed,t}} = 1 \tag{13}$$

In the above equations, $\mathrm{I}_{k',\mathrm{m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{ch}}$ is the smart meter k' ES charge current at node m connected to the phase $\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}}$. Also, $\mathrm{I}_{k'',\mathrm{m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{dch}}$ is the smart meter k'' ES discharge current at node m connected to the phase $\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}}$. For taking into account the RESs , the $\mathrm{I}_{k''',\mathrm{m}}^{\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}},\mathrm{RES}}$ is used to indicates the smart meter k''' RES generation current at node m connected to the phase $\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}}$. Furthermore, $\mathrm{sw}_{\mathrm{k,m}}^{\mathrm{incr,t}}$ and $\mathrm{sw}_{\mathrm{k,m}}^{\mathrm{shed,t}}$ are respectively the switch position for smart meter k at phases $\mathrm{ph}_{\mathrm{incr}}^{\mathrm{m,t}}$ and $\mathrm{ph}_{\mathrm{shed}}^{\mathrm{m,t}}$.

The optimization (12), and its constraints are linear equations. Since decision variables are binary and real, for optimization, the mixed linear programming methods or innovative methods such as genetic or PSO can be used. In addition, the number of switching times can be restricted to extend their lifespan. This constraint can be applied to the decision variables itself or by utilization of the penalty factor in the optimization function. The relevant switching indicators, according to the initial and next states of the connected phase with details of the proposed switching system are listed in Table 1. Also, Figure 2 represents the Connection point assignment system for applying the PR strategy in the smart meters.

3. DISTRIBUTED ALGORITHM

An algorithm is presented in this section to decide the best customers' side strategies that are the load connection points, ESs charging/discharging control, and RESs generation profile management. The procedure of the algorithm shows the interaction between the customers when the suggested way is used in practice. It is explained briefly in Algorithm 1; the smart meters update their consumption current vector via the determined procedure. The recommended procedure is founded on the smart meter abilities such as cloud-enabled features. Actually, the algorithm converges to a number at that the power imbalance will getting as less as predetermined. The innovation of this strategy is its distributed best response structure and optimal performance. Its algorithm in a sample repeat is as follows.

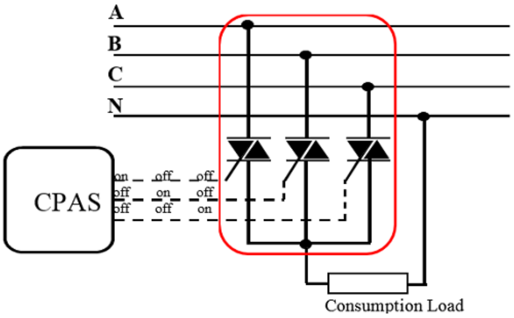

Figure 2. The connection point assignment for PR system integrated into the smart meters

TABLE 1. The Switching Strategies

First State	Next State	(u_j^a, u_j^b, u_j^c)
A	A	(1,0,0)
	B	(-1,1,0)
	C	(-1,0,1)
B	A	(1,-1,0)
	B	(0,1,0)
	C	(0,-1,1)
C	A	(1,0,-1)
	B	(0,1,-1)
	C	(0,0,1)

Algorithm 1. Distributed best response algorithm

```
1-Start
2-Three-phase and neutral voltage vector parameters, load current, amount of RES power generation, charged and discharged power in the ESs monitored and recorded by the smart meter.
3-Smart meter calculates three phases grid current vector.
4-Smart meters send/receive the current vectors with the connected phase number to/from other smart meters in a node.
5-If $\left\| I^{m}_{shed} - I^{m}_{ideal} \right\| < \varepsilon$ , go to Step 2; otherwise, go to the next step.
6-Every smart meter executes the optimization (12) based on the data gathered from Steps 3 and 4 and sends the keep or change control commands to the controller module of Connection point assignment System(CPAS), ES controllers, and RESs management system.
7-CPAS, ES charger/discharger, and RESs Controllers based on the received command perform the operation and smart meters informs the other ones; then go to Step 2.
```

4. NUMERICAL RESULTS

In this section, the performance of the proposed PIM scheme is numerically evaluated. A period of 24 hours is considered. The proposed strategy is implemented in the modified 13-node IEEE sample distribution grid which loaded unbalanced; a four-wire three-phase feeder with isolated neutral, shown in Figure 3. Changes such as adding RESs and an ES unit. RESs are added to nodes 611 and 675, and an ES unit is added to node 652, where the others are kept untouched as the original test feeder.

In the simulation, following Gaussian distributions, 1000 sets of inflexible load data are generated randomly to validate our proposed scheme. The ES capacity is set as 100 kWh and finally, in this simulation, a linear pricing function is selected. Unbalanced power flow calculation in this sample is carried out in form of a forward/backward sweep that has been programmed, executed, and implemented. The optimization has been performed using a linear method. Since the reassignment operation, generation of RESs, and ESs charge managements per node was done individually and is distributed, the execution time for the proposed strategy remains constant as the number of smart meters increases. The neutral current values and the line current values are presented in Table 2 before and after implementing the optimization. As can be seen, the optimal assignment of single-phase loads reduces the peak current in the highly loaded phase. This will increase grid stability plus the possibility of distributing more energy in the grid. Table 2 confirms the considerable dynamically and real-time reduction of unbalanced loading. For example, the mean index value of neutral conductors' current, was reduced above 48%. Figure 4 shows the voltage of the grid's nodes with or without optimization. As it is known, the optimal allocation of single-phase loads causes the balancing of the feeders' current that mitigates the voltage drop at the nodes. In this case, the minimum voltage value increases from 0.98 (PU) to 0.97 (PU). This will reduce the need for reactive power compensation. By optimal managing of the energy storage and allocating some of their capacity to the demand response programs, the grid functioning will be enhanced. In Figure 5, it has been shown that the storages lead to imbalance reductions at node 652 during the day. By implementing this method,

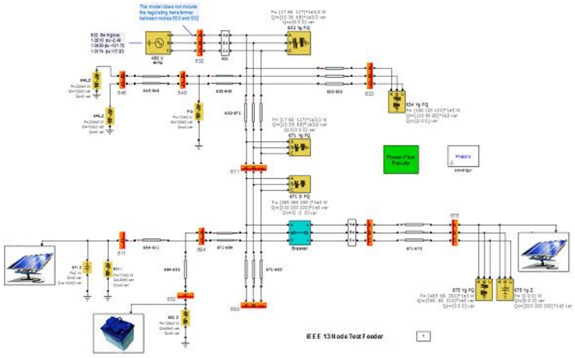

Figure 3. The diagram of the sample grid, a modified version of IEEE 13 Node Test Feeder

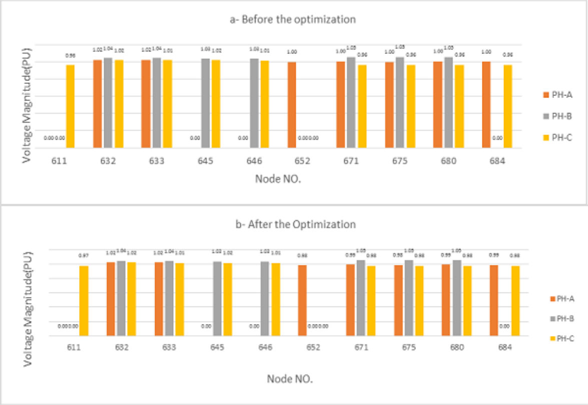

Figure 4. The node's voltage magnitude before and after the optimization

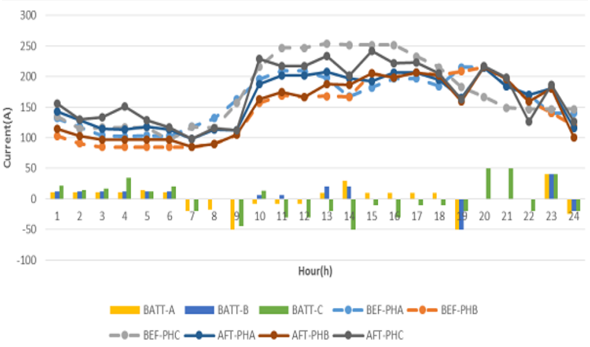

Figure 5. The three-phases feeder current at node 652 with the amount of power charged or discharged in the storages before and after the optimization

TABLE 2. The line current and neutral current values before and after the optimization

		Before Optimization				**After Optimization**			
		N.	**A**	**B**	**C**	**N.**	**A**	**B**	**C**
611	684	71	0	0	71	50	14	0.0	57
632	633	226	79	60	61	94	569	450	538
632	645	19	0.0	143	65	3	71	67	61
632	671	85	0	65	65	60	20	133	52
645	646	64	63	0.0	0.0	45	13	59	52
652	684	299	441	211	522	149	56	6	0.0
671	675	191	202	61	125.9	117	479	254	435
671	680	0	0	0	0	0	164	86	124
671	684	23	63	0	71	15	0	0	0

the current of three-phase feeders is distributed more equally; therefore, the peak current of each distribution feeder significantly reduces due to current reduction in the relatively heavy-loaded phase of it and leads to neutral current mitigation which is apparent in Figure 5. The reduction of the grid's power imbalance also reduce power losses in it, by assuming 20% of all grid's electricity meters were smart and equipped with the proposed strategy, it would reduce from 52KW to 43KW which is about 18% lower.

5. CONCLUSIONS

Load diversities, the different consumption patterns, and increasing penetration of renewable energy resources cause the problem of unbalanced power flow to become more challenging. Moreover, asymmetric three-phase loads or asymmetrical impedances of lines cause an unbalanced grid and excessive and undesirable flow of current in the neutral. In this paper, a novel strategy of rearranging the phases is introduced with a distributed structure, carried out with aid of the facilities in smart grids. The proposed method is based on the optimal assigning of the single-phase customers' grid connection point to one of the phases and also, by controlling the ESs, and managing the RESs generation profiles. Simulation results validated the proposed strategy and demonstrated a considerable reduction in the phase unbalancing and reduction in power losses.

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Persian Abstract

چکیده

در یک سیستم توزیع نیروی برق سه فاز، به علت توزیع ناهمگون بارهای تک فاز، پراکندگی بارها، الگوهای مختلف مصرف و نفوذ فزاینده منابع انرژی تجدیدپذیر در شبکه‌های هوشمند، مسأله پخش بار نامتعادل چالشی تر شده است. در این مقاله، ما یک روش جدید کاهش عدم تعادل فاز ابتکاری که با کمک تخصیص بهینه فاز برای فیدر ورودی ۳ فاز سیستم توزیع نیرو با جابجایی فاز، ذخیره‌سازهای الکتریکی و منابع انرژی تجدیدپذیر، صاحبان کنتورهای هوشمند را تشویق به کمک به اپراتور سیستم توزیع جهت کاهش نامتعادلی فاز می‌نمایند، معرفی کرده‌ایم. این مهم توسط بکارگیری سیستم تخصیص بهینه نقطه اتصال که انعطاف در انتخاب ورودی توان از یکی از ۳ فاز و مدیریت ذخیره سازها و منابع انرژی را دارد، حاصل می‌گردد.نتایج شبیه‌سازی مؤید کارایی این راهکار بوده که نشان می‌دهد مشتریان توانسته اند هزینه‌های خود را کاهش داده و اپراتور سیستم توزیع به افزایش کیفیت توان و کاهش نامتعادلی در توزیع بار دست یافته است.