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Using Game-Theory to Implement an IoT Re-Phasing Algorithm in Smart Grids

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Abstract- The quickest solution towards having a smart grid especially with a strong telecommunication infrastructure is to integrate the conventional electricity meters with IoT services. In this paper, proposing a novel IoT based smart measuring and control systems a non-cooperative game model is developed to implement a sort of load balancing commands as a DR program activity. Depending on the level of the grid imbalanced current, all three phase customers can participate in and take actions from the smart re-phasing program which has been developed into the proposed algorithm. Telecommunications and sharing information between smart meters are essential to the algorithm because of its distributed structure which makes it computationally tractable. The proposed approach provides a new paradigm for modeling and sets different prices which are computed based on the neutral current value to all grids' nodes. Re-phasing operations can be done where smart meters are installed and hence any customer can competitively participate in lowering neutral current of the network based on a market mechanism. The performance of the proposed model is evaluated through performing a number of simulations on a typical smart grid inclusive of 123 nodes and 1024 consumers. The results imply that the propose strategy poses a good and reliable properties in balancing distribution system, mitigating neutral currents as well as peak load reduction.

Keywords: IoT, Load balancing, Re-phasing, Demand response, N-Person non-cooperative game.

1. Introduction

In many countries a 3-phase four wire network is used to supply the required power of consumption loads. The consumers are often connected to the network through a single phase service. Distribution system operators make a great effort to equitably distribute all customers among three phases of the system in order to minimize the imbalanced current passing to the neutral wire. However, the loads are not always identical in their types and the consumption patterns among electricity customers are different. These are some main reasons a power distribution system is usually operated in an unbalanced condition; furthermore, asymmetrical distribution grid structure can worsen the unbalanced power conditions. These factors are the origins of various problems such as unequal occupying grid's serving capacity among three phases, increasing voltage unbalances, increasing power losses and making some equipment overloaded. Therefore, lower loaded phases have to follow the heaviest loaded phase limits, such as the maximum loading and protection criteria. On the other hand, being power loss proportional to square of current, balancing feeders would significantly lead to power loss reduction. Obviously, by mitigating neutral current, power loss in neutral conductors is also dramatically reduced. As the distribution loads are mostly single-phase, the majority of them could be a connection-point changeable among three phases. In some papers, the traditional phase assigning methods have been studied [1]. It introduced a model of using mixed integer linear programming for phase swapping involving nodal and lateral connections. The re-phasing combination produces a huge number of possible states; therefore, optimization algorithms with search-based methods are well suited. Suggesting heuristic optimization load balancing methods has been done using genetic algorithm in [2] and Immune algorithm in [3]. [2] clarifies the existence of a high neutral current brings out difficulties for the detection of earth faults by the protective relays, ergo implements an NSGA-II application for the re-phasing. In [3], a re-phasing strategy is evaluated by an immune algorithm (IA) considering a multi-objective function which is composed of three terms: cost of imbalanced current, the customer service interruption cost, and labour costs. Moreover, in [4], a new method of phase balancing approach is offered based on the combination of the bacterial foraging and particle swarm optimization algorithms. It is applied to unbalanced radial and meshed distribution grid. The fuzzified objectives in the strategy are the neutral current of the supporting feeder, re-phasing costs, amount of voltage drops, and line losses. In [5], an expert system is implemented for the re-phasing approach to diminish the neutral current of the candidate distribution feeders. However, in [6], it is perceived in some conditions, because of existence of voltage-dependent loads in the network, the phase-balancing gives rise in power losses despite its target for lessening. In order to improve circuit losses, the authors in the paper [7] propose an algorithm for re-phasing of imbalanced large-scale radial distribution systems with single and double-phase laterals. In [8] a substation connecting to single-phase loads, generation, and energy storage is considered. The presented algorithm minimizes the operation cost of the system with balancing the loads with the aid of energy storage. A dynamic phase balancing by optimal location finding of the re-phasing switches is investigated in [9] and applicable when the imbalance factor is more than a preferred value. The paper [10] suggests classifying any set of three-phase power series into one of four scenarios if there are a definite maximum phase, a definite minimum phase, or both. Its main contribution is to present a new technique to decompose three-phase power series into a random and systematic imbalance component.

To comply with the easing of green energy and respecting low emission power generation, penetration of DGs and ESs into the distribution network has increased worldwide which consequently requires new methods for grid analysis. In recent years, many studies have been conducted in this subject [11-16]. In [17], a strategy based on a multi-objective optimization formulation has been developed for scheduling of the unbalanced micro-grids. The objective functions are defined on the specific services and necessities associated with the micro-grid operation, such as operation costs, power quality enhancement, and energy saving criteria. Paper [18] manages phase unbalance condition with respect to the connection of numerous single-phase solar generators and single-phase loads to a three-phase distribution system. In that paper, a probabilistic model and a genetic algorithm have been utilized. Furthermore, in [19], a stochastic multi-objective framework for a three-phase distribution grid is organized to concurrently minimize the active power losses and the level of voltage unbalance of the network. The reactive power output of solar converters is used to fulfil the objectives. The spread of distributed energy resources (DERs) at distribution and prosumer/grid-edge points engenders operational concerns. Besides conventional relief and protection schemes, the prerequisites such as phase balancing, grid-edge reactive and voltage support are coming into view [20]. Re-phasing can be supplemented by feeder reconfiguration or DG placement algorithms. A simultaneous optimization approach is presented in [21]. In [22], a smart distribution feeder has been studied in deterministic and stochastic structures and got balanced by DG sizing and re-phasing approach at the same time.

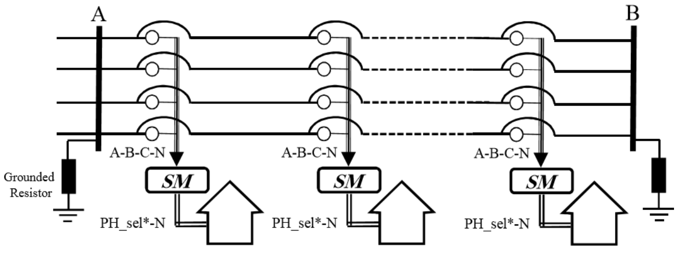
Most of the re-phasing techniques are offline. In other words, the pattern of phase allocating to customers is obtained from offline procedures including power flow studies. It is well known that the consumption loads are varying on a timely basis and hence a tool with the capability of real-time analysis is more desirable in load balancing procedures. Specified power electronic devices perform the load balancing by injecting the compensating apparent power components into the distribution grid in real-time [23]. Besides, [24] presents a new approach to mitigate the phase unbalance of lines. A novel winding connection in the ordinary two-winding transformers is introduced to provide real-time switch-less operation. In forthcoming smart grids, the power suppliers can amend the customers' load profile by applying proper DR programs using smart meters [25]. Through smart meters, users encompass access to the electricity consumption and the price data, enabling them to take part in DR programs [26]. A lot of research has discussed in the context of smart grids' communications needing secure and reliable links between the utilities and the devices with a high quality of service. Nowadays, the brilliant specifications of low power, long range, and high capacity of the low power wide area network (LPWAN) technologies bring about a new solution for it based on the Internet of Things (IoT) [27].

The internet has positively reformed the ways of solving numerous existing problems. Nowadays, major numbers of modern electrical appliances such as television already integrated with internet connectivity which can allow them to communicate for sending data and information or receiving commands. Most of them could be controlled and monitored remotely, for instance via cloud-based interfaces. The past has now developed through the internet. The Internet of Things or IoT is making industries and businesses much smarter. The electrical power industry is not an exception. Over the years, it has been facing many innovations and technological development which one of them is Internet integration. With the IoT, we could address various problems in electrical power systems. When it comes to the demand response programs, IoT definitely plays a fundamental role. Through the IoT, customers can behave about the electricity in an ideal manner. They are interconnected with each other to participate in DR programs. Through developing paradigm of the Internet of things, IoT-enabled smart buildings could be maintained by an associated and cost-effective IoT application at user-level [28]. In [29], contingency management is done with the aid of IoT. Furthermore, the economic feasibility of a phase reconfiguration method mitigating the unbalance influence of plug-in electric vehicles in terms of reliability and power quality on the secondary distribution system is studied in [30].

The Smart grid, as an IoT application on the utility side, gathers and scrutinizes on energy and related information about it to elaborate the electricity distribution conditions. Advanced metering infrastructure (AMI) devices offer smart grid's end-users electric power-related data as well as devices of distribution automation. IoT driven smart meters as a part of AMI devices are the smart meters integrated with the internet in order to communicate with the users or other devices online. With the internet connectivity, the IoT smart meters do not necessarily need another dedicated physical communication links and infrastructure. They communicate based on the internet and have Plug and Play (PnP) features, therefore, are easy to be registered on the grid. Subsequently, upgrading the IoT smart meters to accommodate more types of applications need often no further hardware changes, if ever needed are for the structure of the electric parts, for example, a power switch. In this paper, we introduce a novel smart scheme based on Game-theory and IoT principles to mitigate the phases' unbalance. The re-phasing is done at the customer premises by smart meters, which are programmed and designed to be a processor and a connective link based on the IoT system. As a result, the main feeder which supplies customers equipped with these smart meters will be optimally got balanced. The customers are IoT-enabled and able to share data with each other. The IoT is an important part of this scheme and because of it, the physical direct links between the customers are eliminated. This paper considers the IoT aspect of the smart meters and tries obtaining possible answers to optimal load balancing through applying the game-theory framework. The rest of this paper is organized as follows. In Part II, the system model is demonstrated, and the load balancing problem is formulated as the customers' game. In Part III, a distributed procedure is recommended to specify the NE (Nash Equilibrium). In part IV, outcomes are given, and the efficiency of the proposed novel strategy is evaluated. Furthermore, the conclusions are provided in the last part V.

2. SYSTEM MODEL

Assume a smart grid with the 4-wire distribution feeders which one of them is shown in Fig. 1. The smart meters have 3 phase input with the neutral which only one of the three phases based on the strategy described below will be optimally selected. In the following, we will simulate the system and consumer sides in the proposed strategy.



*PH_sel=A or B or C.

Figure 1. Diagram of a 4-wire distribution feeder with its customers and the integrated proposed smart meters.

A. The neutral Current

The neutral current in the four-wired and earthed distribution systems is a popular topic in the research activities. The primary frequency component of it is mostly due to the unbalanced loads and inequality in the grid's impedance. Furthermore, in a secure distribution system, the earthing resistors of the neutral system should be low enough in order not to overrun the specific level of neutral to earth voltage because of the neutral current as a result of the load imbalance. With the introduction of smart grid, it is assumed that the residential buildings also possess photo-voltaic systems. The increasing implementation of single-phase residential DG systems will cause imbalance and increase the current value of neutral wires even in the case of full load balance in the system. As may be expected in these buildings using power storage systems could solve it and make the power usage flexible.

A sample feeder with three phase wires and one neutral wire that supply the buildings which are integrated by the proposed smart meters is shown in Fig. 1. The neutral current vector in a four-wired earthed distribution system is obtained based on (1) at each node.

$$\overrightarrow{I^{n}_{m,net}} = -\left(\overrightarrow{I^{a}_{m,net}} + \overrightarrow{I^{b}_{m,net}} + \overrightarrow{I^{c}_{m,net}}\right) \tag{1}$$

We have:

$$\overrightarrow{I^{p}_{m,net}} = \sum_{r_m \in M_m} \overrightarrow{I^{p}_{r_m,net}}, \quad p \in \{a,b,c\} \tag{2}$$

where $\overrightarrow{I^{p}_{r_m,net}}$ is formulated as (3):

$$\overrightarrow{I^{p}_{r_m,net}} = \frac{P^{p}_{r_m,L} + P^{p}_{r_m,ch} - P^{p}_{r_m,dch} - P^{p}_{r_m,PV}}{\left(V^{p}_{re,m} + V^{n}_{re,m}\right) - j\left(V^{p}_{im,m} + V^{n}_{im,m}\right)}$$

$$- j\frac{Q^{p}_{r_m,L} + Q^{p}_{r_m,ch} - Q^{p}_{r_m,dch} - Q^{p}_{r_m,PV}}{\left(V^{p}_{re,m} + V^{n}_{re,m}\right) - j\left(V^{p}_{im,m} + V^{n}_{im,m}\right)} \tag{3}$$

In (1)-(3), let $M_m = \{1,\ldots,M_m\}$ denotes the set of customers in node m that $r_m \in M_m$ indicates one of them $\overrightarrow{I^{n}_{m,net}}$. is the neutral current vector at node m and $\overrightarrow{I^{p}_{m,net}}$ consists of $\overrightarrow{I^{a}_{m,net}}$, $\overrightarrow{I^{b}_{m,net}}$, and $\overrightarrow{I^{c}_{m,net}}$ that are the net current vectors of the phases a,b,c at node m respectively.

$P^{p}_{r_m,L}, P^{p}_{r_m,ch}, P^{p}_{r_m,dch}$ and $P^{p}_{r_m,PV}$ are respectively the load active powers, storage charge/discharge, and PV power output of the customer r_m on the phase p. $Q^{p}_{r_m,L}, Q^{p}_{r_m,ch}$, $Q^{p}_{r_m,dch}$ and $Q^{p}_{r_m,PV}$ are the reactive powers for them. $V^{p}_{re,m}$ and $V^{p}_{im,m}$ are the real and imaginary components for the phase or neutral voltages at node m.

The values of $P^p_{r_m,PV}$ and $Q^p_{r_m,PV}$ differ according to the several parameters such as the installed capacity, efficiency of the photovoltaic module or the inverter, the installation place, and etc. In this paper, the mentioned values are intended according to buildings contractual power. Moreover, the amount of charging or discharging power to/from the storage systems like the photovoltaic generation relied on many parameters such as the storage capacity, initial capacity, charge or discharge power, efficiency, and etc. By optimal management of energy storages and allocating some of their capacity to DR programs, grid operational state would be enhanced. As the capacity of energy storages are limited, scheduling needs load consumption prediction to determine optimal time of charge/discharge and its amount. Taking it into consideration guarantees the storage could be responsive when is required to flex for demand. In addition, electricity rates should be considered for optimal operation of electricity storages.

In this paper, we proposed an index to indicate all the neutral conductors' current state in a distribution system. It is derived by the mean index value of the neutral conductors current (NCF) which is defined as below:

$$NCF = \sqrt{\frac{\left(I^n_1 + I^n_2 + \ldots + I^n_L\right)}{L_n}} \tag{4}$$

In (4), I^n_l is the magnitude of neutral current on feeder $l \in \mathcal{L}$ and let $\mathcal{L} = \{1, 2, \ldots, L\}$ denotes the set of feeders with a neutral conductor in the grid and $\mathcal{L}_n$ is the total number of them.

B. The Game-theory Framework

The grid sets the electricity price per customer and broadcasts the price information to the Smart meters. Then the customers reply to the given price by selecting their connection point to maximize their benefits. As the grid acts first and then the customers make decisions based on the given prices, the nature of such an interaction fits into the Stackelberg game. It provides a paradigm for modeling such a scenario. In the Stackelberg game, the smart grid is the leader and the smart meters are the followers because their reactions are built based on the decision of the smart grid.

To determine the optimal phase assigning, it is assumed the customers are profit maximizers and price anticipating knowing the electricity price is calculated from (5) that mitigating the neutral current reduces it. The electricity price function is formulated as below:

$$\overset{+}{\pi}_m(t) = \pi_m(t) + \alpha_m(t)\ .\left|\overrightarrow{I^n_{m,net}(t)}\right| \tag{5}$$

Let $\{1, 2, \ldots, T\}$ is the set of time slots. $\pi_m(t)$ is the base electricity price at node m at time t, $\alpha_m(t)$ is the penalty factor and $\overset{+}{\pi}_m(t)$ is the projected price depending on the $\left|\overrightarrow{I^n_{m,net}(t)}\right|$ magnitude of neutral current vector at node m at time t.

As the neutral current at each node depends on the consumption pattern of all customers connected to it, therefore, the customers' difference is showed as a non-cooperative game.

By substituting (2) to (1), we have:

$$\overrightarrow{I^n_{m,net}} = -\sum_{p\in\{a,b,c\}} \sum_{r_m \in M_m} \overrightarrow{I^p_{r_m,net}} - \sum_{p\in\{a,b,c\}} \overrightarrow{I^p_{j,net}} - \sum_{p\in\{a,b,c\}} \sum_{r_m \in M_m, r_m \neq j} \overrightarrow{I^p_{r_m,net}} \tag{6}$$

The consumers' houses are equipped by proposed smart meters that can intercommunicate with the DSM Centre and each user based on IoT.

Let $\sum_{p\in\{a,b,c\}} \overrightarrow{I^p_{j,net}}$ is the load vector of customer j in node m, at time slot t. However, each customer such as j aims to locally choose its connection point denoted by $S_j(t)$ to maximize his/her payment.

In the customers' competition, the smart devices are the actors, the load connection patterns $S_j(t), j \in M_m$ are the plans, and the utility function of consumer j is (7):

$$U_j\left(S_j(t), S_{-j}(t)\right) = \alpha_m(t).\left|\sum_{p\in\{a,b,c\}} \overrightarrow{I^p_{j,net}} + \sum_{p\in\{a,b,c\}} \sum_{r_m \in M_m, r_m \neq j} \overrightarrow{I^p_{r_m,net}}\right| \tag{7}$$

Where $U_j\left(S_j(t), S_{-j}(t)\right)$ means the utility function of the energy customer j and $S_{-j}(t)$, the switching state vector of other customers, is defined as:

$$S_{-j}(t) = \left(S_1(t), \ldots, S_{j-1}(t), S_{j+1}(t), \ldots, S_{M_m}(t)\right) \tag{8}$$

Equation (7) implies that the utility of customers dependent on the sum of load current vectors of electricity customers. Moreover, the resultant formula of the two vectors can be employed in (7) to separate the load current vector of a customer from the other.

The switching strategy for customer j in NE is indicated with $S^*_j(t)$. It is the resolution of the subsequent optimization issue when other clients' connection points are stabilized.

$$S^*_j(t) \in argmax\ \ U_j\left(S_j(t), S^*_{-j}(t)\right) \tag{9}$$

Where $S^*_{-j}(t)$ is the vector of switching strategy pattern of other consumers in Nash equilibrium.

In the NE, no player would want to change her/his strategy if she/he knew what strategies the others were following. In other words, none of the customers has a motivation to change its best phase while the others are without change, since all the customers in the Nash equilibrium simultaneously play the best responses to each other's strategies.

This method offers an outline to study and progress a suitable way for assigning loads to one of the three phases of a feeder in smart grid distribution system in order to determine the optimal connection points. The customers playing a non-cooperative game which is a N-person game. In this method, the players try the play a game to reduce their marginal price to reduce their bill costs, At an Nash equilibrium point all the customers have chosen their connection point to the feeder and nobody of them will get benefit from unilaterally deviating from it. In the appendix part we proof the uniqueness and existence of the Nash equilibrium.

C. The switching Strategy

Fig. 2 depicts the connection point assignment system (CPAS) in which the solid-state switches connects the consumer to one of the three phases. It is worth mentioning that the switches should be compatible with the expected current of their consumer.

In this case, it is assumed that the smart meters have a 3-phase input that enabled by the controller module establishing the connection to one of the input phases. The performance logic of the system is that at any time instant, only one of the three switches is on and the others are off. Since loads of single-phase customers are not pure Ohmic and include inductive values, therefore the switching and phase reassignment should be carried out in such a way that the inrush current or DC offset current does not appear.

The proposed method is based on the strategy of φ switching [31] that re-phasing is done with the aid of its switching logic. The current obtained after changing the phase connection point has a direct offset component and a constant component that is reached by Laplace transform and Convolution integral:

$$i(t) = \frac{\dfrac{v}{\sqrt{R^2 + L^2.\omega^2}}}{\sin(\omega t + \varphi_0 - \phi) - \sin(\varphi_0 - \phi)e^{(-t/\tau)}} \qquad (10)$$

And the voltage of the prior connected phase at the changing time t equals to:

$$v = \hat{v}.\sin(\omega t + \varphi_0) \qquad (11)$$

In 10 and 11, $\hat{v}$ is the peak voltage, ω is the angular frequency, φ_0 is the initial voltage phase at the switching time. R and L are the Ohmic and inductive values of load impedance respectively. ϕ equals $\tan^{-1}\frac{\omega L}{R}$ and $\tau = \frac{L}{R}$ is the time constant.

As can be seen in (10), if the switching takes place at a time when $\phi = \varphi_0$, there will be no transient value and the current will be continued without interruption.

Finally, the current consumption vector of each customer is a function of switching strategies being calculated based on (12) at iteration $k+1$ in time slot t .

$$\overrightarrow{I_j^{k+1}}(t) = \overrightarrow{I_j^{k}}(t) \times \begin{bmatrix} \left(\left|u_j^{a^k} . u_j^{b^k}\right|\right).1\angle\left(\left(u_j^{b^k} - u_j^{a^k}\right).\dfrac{\pi}{3}\right) + \\ \left(\left|u_j^{c^k} . u_j^{a^k}\right|\right).1\angle\left(\left(u_j^{a^k} - u_j^{c^k}\right).\dfrac{\pi}{3}\right) + \\ \left(\left|u_j^{b^k} . u_j^{c^k}\right|\right).1\angle\left(\left(u_j^{c^k} - u_j^{b^k}\right).\dfrac{\pi}{3}\right) + \\ \left(u_j^{a^k} + u_j^{b^k} + u_j^{c^k}\right) \end{bmatrix} \qquad (12)$$

where $u_j^{a^k}, u_j^{b^k}, u_j^{c^k}$ are the binary values, $\in\{0,1\}$, and indicate switching strategies of customer j at iteration k. As mentioned before, at each time instant $t \in T$ only one of the three above strategy is 1 and others get 0. In other words, there exists only one on-switch for each strategy and according to the Boolean nature of the decision variables (switching strategies), the (13) should be considered for each customer such as j:

$$u_j^a(t) + u_j^b(t) + u_j^c(t) = 1, \quad \forall t \in T \qquad (13)$$

According to the initial and next states of the connected phase the relevant switching indicators are defined. Details of the proposed switching scheme are listed in Table I.

Table I.THE SWITCHING STRATEGIES.

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

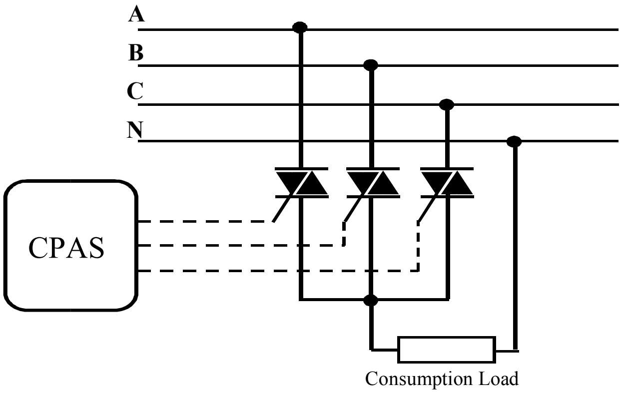


Figure 2. The Connection point assignment system integrated in the smart meters.

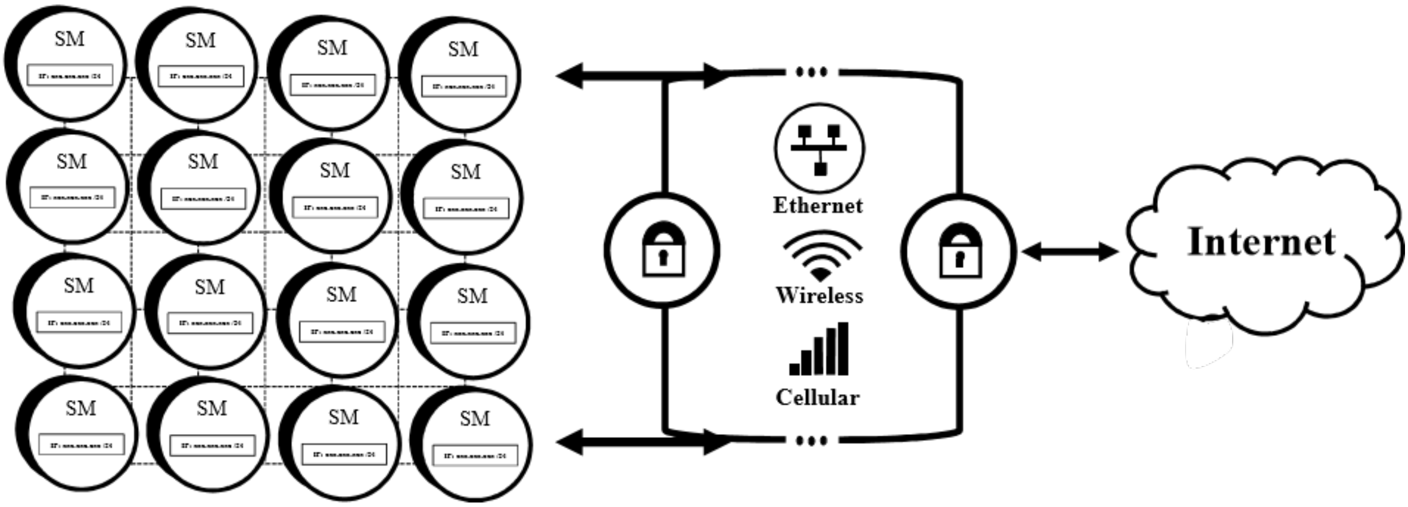


Figure 3. The IoT platform of the smart meters.

D. The IoT platform

In Fig 3, the IoT platform is illustrated. Each smart meter is assigned by an appropriate IP, public, when has access to the internet, otherwise a private one. It needs also the subnet mask for defining the range of IP addresses operating in an identical network.

In the proposed scheme, all the smart meters installed in a grid node are placed in a communication network being able to interact each-other without the necessity to a layer 3 router, through the layer 2 - data link layer. The connection among them can be established in Ethernet, wireless or cellular environments. It is encrypted to prevent unauthorized access by means of Data encryption solutions. As well as internal links among smart meters, they could be accessible by the internet which is done by the layer-3 devices putting them on the net. Obviously, if the smart meters have internet access, there is no need to establish separate communication infrastructure for linking them together.

From the vantage point, if there were no internet connection for the smart meters, the communication structure for M of them would need $\binom{m}{2} = \frac{m\times(m-1)}{2}$ number of direct links. Therefore, the crucial point of implementing the IoT is eliminating the needs of them. Besides, adding a new smart meter needs to install new links which in the absence of IoT is time-consuming and costly and in some conditions, it may be infeasible. Finally, with the aid of IoT implementation, installing the proposed strategy software for smart meters will be facilitated as they could be programmed and upgraded via the internet or using cloud-based applications.

3. DISTRIBUTED ALGORITHM

An algorithm is introduced in this part to decide best customers' side game strategies that are the load connection points. This procedure shows the interplay between the consumers when the recommended way is used in practical smartgrid systems. k is the repetition amount and $S_j^k(t)$ denotes the switching strategy of customer j at repetition k at period t. The interplay among any smartmeter and the power supplier is presented in Fig. 4. In every repetition, the smart meters refresh their fee.

The algorithm of smart devices is briefed in Algorithm 1. In the first row of it, smart devices communicate with each other for data exchange specifically the consumption current vector tagged by appropriate ID. The Lines 2 to 6 describes the optimal re-phasing strategy. Within this loop, each smart meter selects and tries all the switching schemes from Table I that are consistent with the current state. The electricity price according to (5) is calculated for the selected switching pattern in line 3. In line 4, each smart meter shares the price which has been calculated in line 3 to the others. Next, in line 5, the algorithm computes the switching strategy with the highest utility $U_j^k(t)$ based on (7) by comparing the received prices with its price. Considering equation (7), the smart meters need the updated status of the other players (smart meters). However, it does not need the switching pattern decisions made by the other customers since only depends on its load and the previous statuses of the customers. This fact guarantees the edge computing's ability of the smart meters. Finally, in line 6, the smart meter carries out the re-phasing procedure according to the computed switching strategy in line 5. At the end of this algorithm, the smart meters update their consumption current vector and broadcast it to the others. The recommended procedure is founded on the game-theory technique.

Actually, the algorithm converges to a number at that customers are playing their equilibrium strategy based on the load profile data. In the equilibrium, none of the customers can gain benefit by deviating from the chosen strategy.

: Algorithm 1. Executed by customer *j* at time slot T in iteration *k

1: Communicate and exchange its and the others' consumption data tagged by ID via IoT.

2: Find the switching schemes consistent with the current state according to Table I.

3: Calculate the electricity price for the designated optimal switching pattern based on (5).

4: Share the nominated electricity price among the customers similar to Fig. 4.

5: Compare the received others' prices with its nominated price.

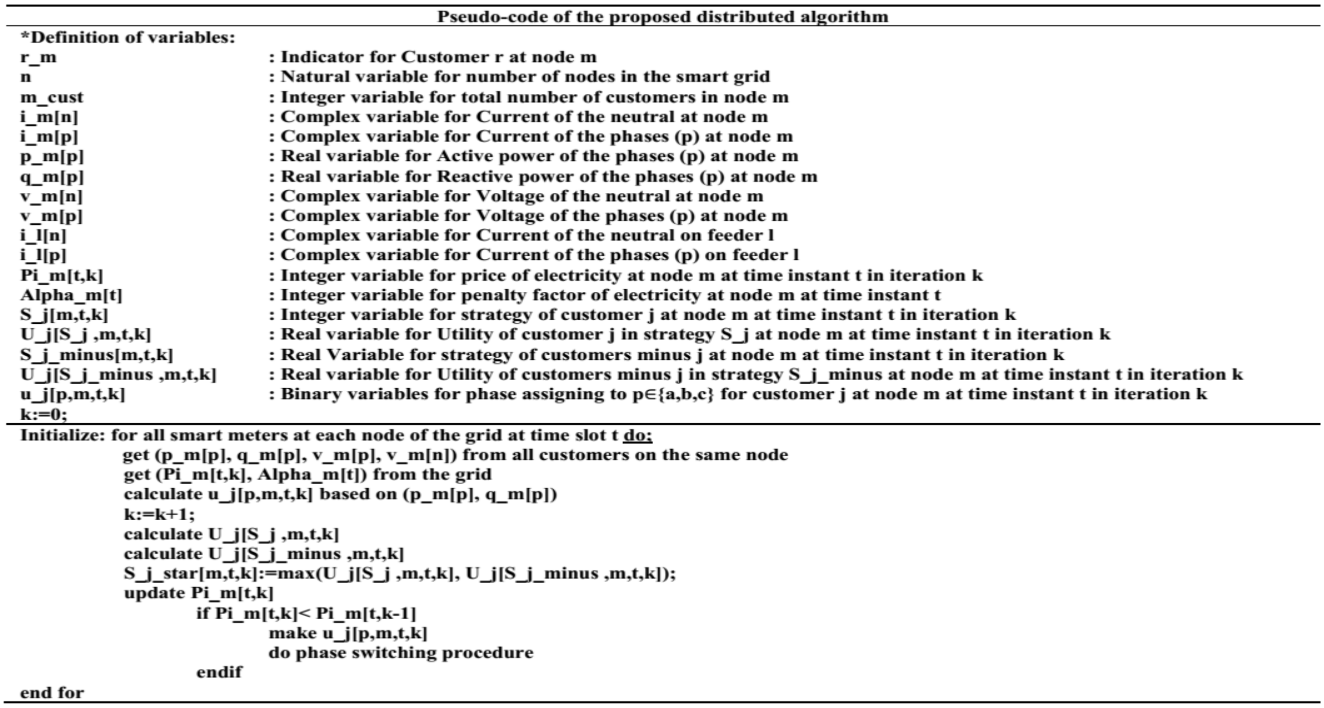
6: Carry out the switching procedure.

7: Update and broadcast the new consumption vector.

***: Next iteration till the end of the DR period.**

Algorithm 1: The proposed algorithm description executed by the smart meters.

For better clarifying the proposed distributed algorithm, we insert the pseudo-code of it to Fig. 5. As it can be seen in Fig. 5, it is very easy to implement it on popular programming languages even the open-source ones are able to handle.



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Pseudo-code of the proposed distributed algorithm
*Definition of variables:
r_m                     : Indicator for Customer r at node m
n                       : Natural variable for number of nodes in the smart grid
m_cust                  : Integer variable for total number of customers in node m
i_m[n]                  : Complex variable for Current of the neutral at node m
i_m[p]                  : Complex variable for Current of the phases (p) at node m
p_m[p]                  : Real variable for Active power of the phases (p) at node m
q_m[p]                  : Real variable for Reactive power of the phases (p) at node m
v_m[n]                  : Complex variable for Voltage of the neutral at node m
v_m[p]                  : Complex variable for Voltage of the phases (p) at node m
i_l[n]                  : Complex variable for Current of the neutral on feeder l
i_l[p]                  : Complex variable for Current of the phases (p) on feeder l
Pi_m[t,k]               : Integer variable for price of electricity at node m at time instant t in iteration k
Alpha_m[t]              : Integer variable for penalty factor of electricity at node m at time instant t
S_j[m,t,k]              : Integer variable for strategy of customer j at node m at time instant t in iteration k
U_j[S_j ,m,t,k]         : Real variable for Utility of customer j in strategy S_j at node m at time instant t in iteration k
S_j_minus[m,t,k]        : Real Variable for strategy of customers minus j at node m at time instant t in iteration k
U_j[S_j_minus ,m,t,k]   : Real variable for Utility of customers minus j in strategy S_j_minus at node m at time instant t in iteration k
u_j[p,m,t,k]            : Binary variables for phase assigning to p∈{a,b,c} for customer j at node m at time instant t in iteration k
k:=0;
Initialize: for all smart meters at each node of the grid at time slot t do;
            get (p_m[p], q_m[p], v_m[p], v_m[n]) from all customers on the same node
            get (Pi_m[t,k], Alpha_m[t]) from the grid
            calculate u_j[p,m,t,k] based on (p_m[p], q_m[p])
            k:=k+1;
            calculate U_j[S_j ,m,t,k]
            calculate U_j[S_j_minus ,m,t,k]
            S_j_star[m,t,k]:=max(U_j[S_j ,m,t,k], U_j[S_j_minus ,m,t,k]);
            update Pi_m[t,k]
                    if Pi_m[t,k]< Pi_m[t,k-1]
                            make u_j[p,m,t,k]
                            do phase switching procedure
                    endif
end for
```

Figure 5. The pseudo-code of the proposed distributed algorithm.

4. PERFORMANCE EVALUATION

The proposed method was applied on a 123-node distribution grid loaded unbalanced. The diagram of the grid is shown in Fig. 6. It is an unbalanced smart grid having 1024 customers that 20% of them are integrated with the proposed approach. Firstly, we need a platform for power flow analysis with and without implementing the strategy. In this paper, unbalanced power flow has been carried out based on the way introduced in [32] which is in form of the forward/backward sweep and based on the Newton-Raphson method.

Besides, the optimization belongs to the proposed distributed algorithm for the re-phasing strategy has been performed using the branch and cut linear method. Since the re-phasing operation per node was done separately and was distributed, the execution time for the proposed approach remained constant as the number of smart meters increased.

The line current values are presented in Fig. 7 before and after implementing the proposed load balancing strategy. As can be seen, the current of three-phase feeders is distributed more equally and its neutral current is mitigated which is apparent in Fig.8. The neutral current values are presented in Fig. 8 before and after applying the approach that confirms the significant dynamically and real-time reduction of the unbalanced loading. The mean index value of the neutral conductors' current (NCF) was alleviated more than 48% based on 4. It proved the efficiency of applying this method to mitigate the neutral current. Moreover, current reduction in the heavy loaded phase by optimal re-phasing would reduce the peak current of the feeders.

As shown in Fig. 7 the peak current of the feeders has reduced significantly. The reduction of feeders' peak current demonstrate the efficiency of the distributed algorithm in decreasing the loading on distribution stations and equipment such as transformers, capacitors, regulators, and etc. It would increase the grid stability as well as the opportunity of distributing more energy in the grid.

Fig. 9 presents the three-phase current values at the grid's nodes. Similar to the feeders, the nodes are positively affected by applying this strategy in load balancing. Furthermore, Fig. 10 states the voltage of the grid's nodes with or without optimization. Obviously, optimal assigning of single-phase loads causes balancing of the feeders' current and peak reduction that intuitively mitigates the voltage drop at the nodes. In this case, the minimum voltage value increases from below 0.94 (PU) to near 0.95 (PU) that it would reduce the need of reactive power compensation. By participating in the proposed strategy, the customers benefit from the reduction in their electricity bill.

In Fig. 11 , the daily electricity bill for customers 1–10 in node 83 with and without implementing the proposed strategy is shown verifying customers can save by participating in this approach. The load balancing would also reduce power losses. In this case, by implementing the strategy and assuming 20% smartness of all meters, the power losses at peak hour reaches from 52KW to 43KW which is about 18% lower. For higher penetration of the proposed smart meter the advantages of it will be more recognized for example power losses would be more reduced.

Fig. 12 illustrates the power losses based on the ratio of the number of smart meters to the total number of all meters.As it can be seen by increasing the number of customer to 2/3 of total is sufficient, because when 2 phases of 3 phases are optimally selected, automatically the last phase would be optimal.

To verify the efficiency of our algorithm, we compare it with applying the switching strategy schemes on Binary Genetic optimization method.

As the decision values are the connection points of the phases, the output result was as same as the proposed algorithm, consequently we ignore to publish them to avoid blathering.

The approach increased the customers' utility, reduced the phases' unbalance, and also improved the power quality state of that case. In the end, in this research, we showed that the proposed strategy has an acceptable presentation with its own advantages and can be utilized in smart grids.

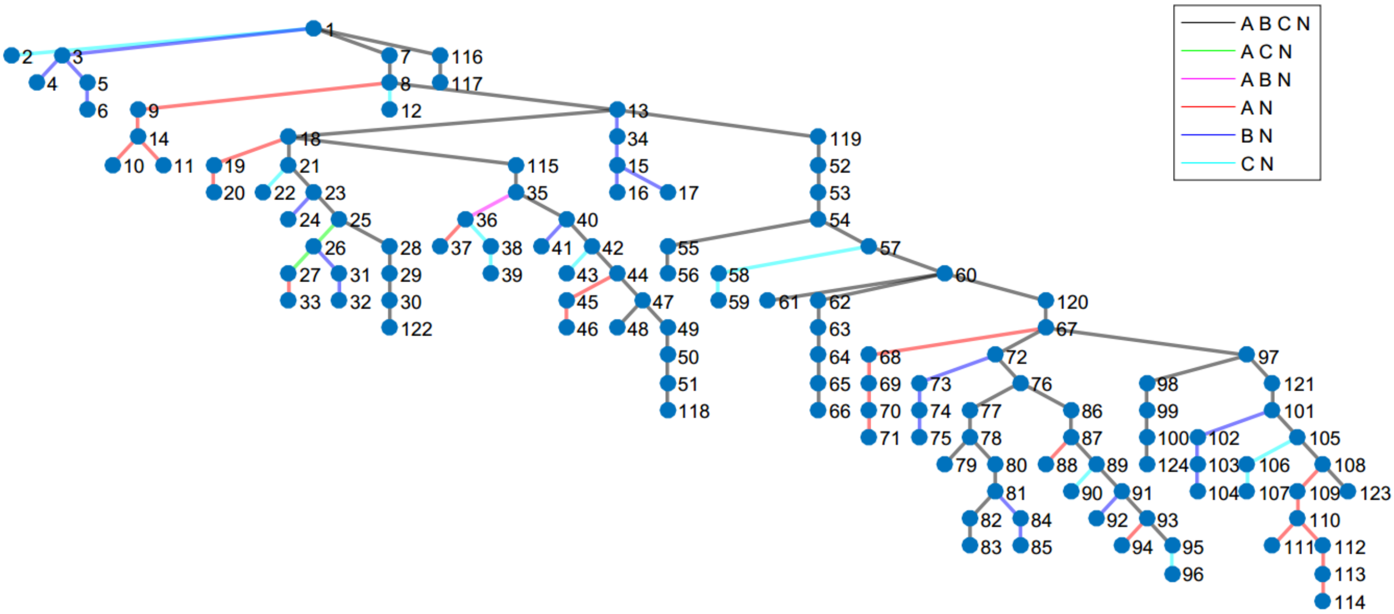

Figure 6. The 123 node test feeder case with configuration specifications.

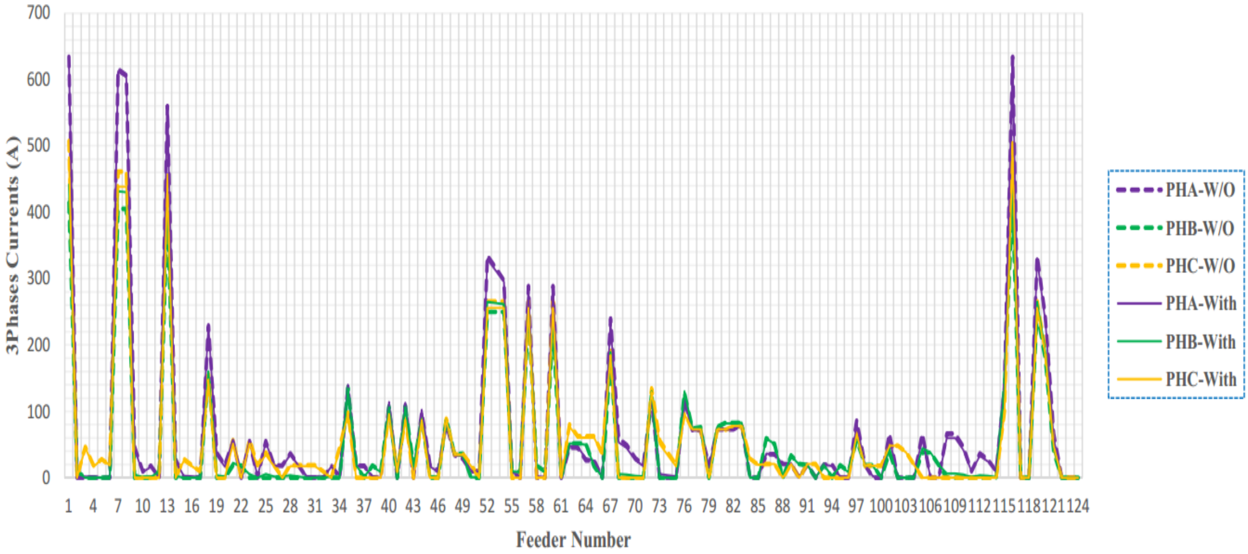

Figure 7. The feeders' 3 phase current with and without the proposed smart meters.

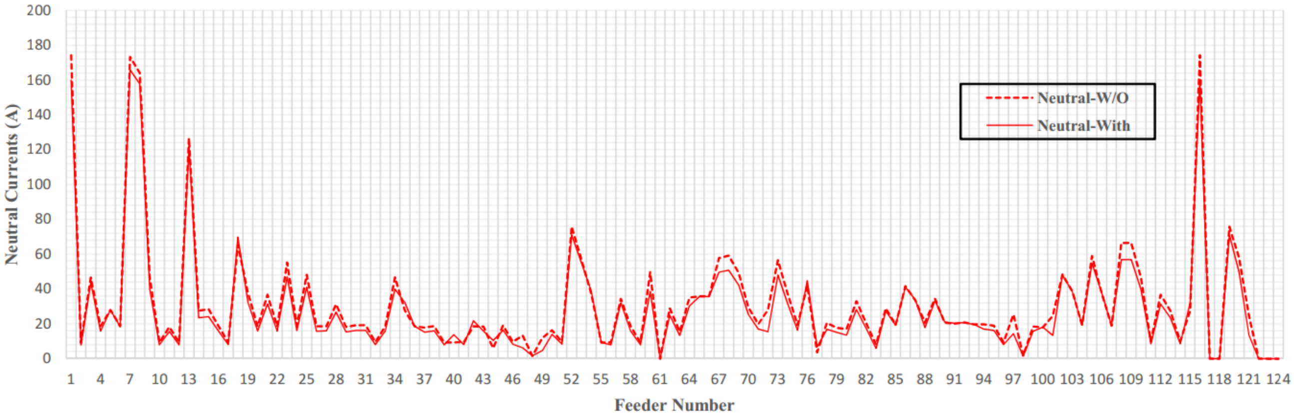

Figure 8. The neutral currents of different feeders with and without the proposed smart meters.

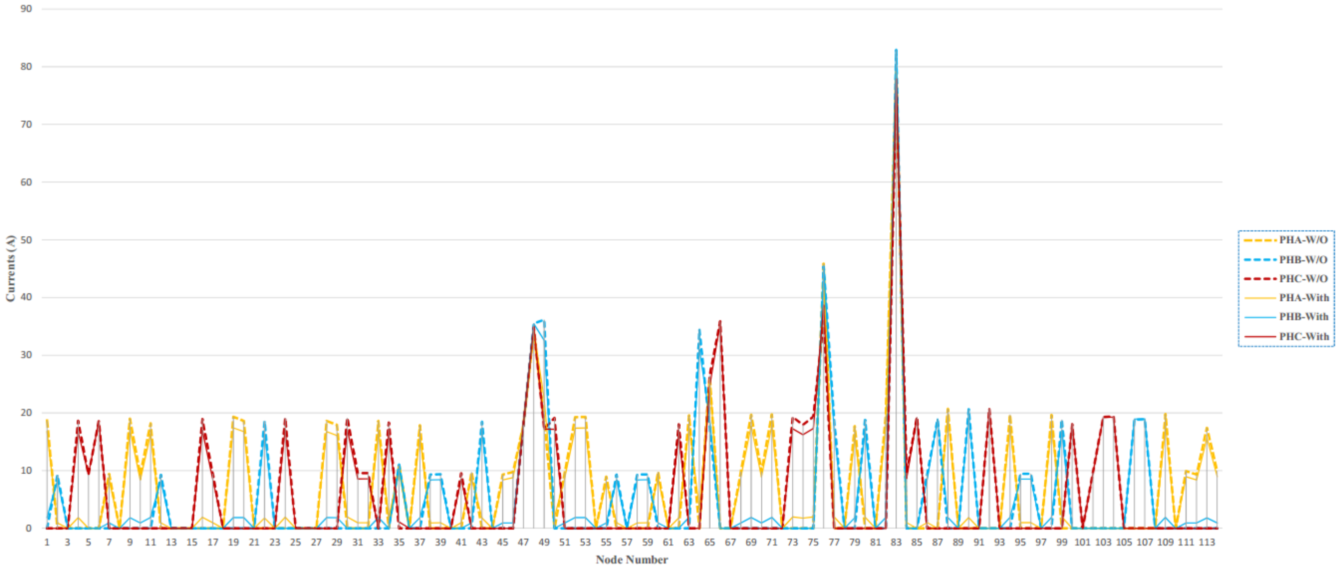

Figure 9. The nodes' 3 phase current with and without the proposed smart meters.

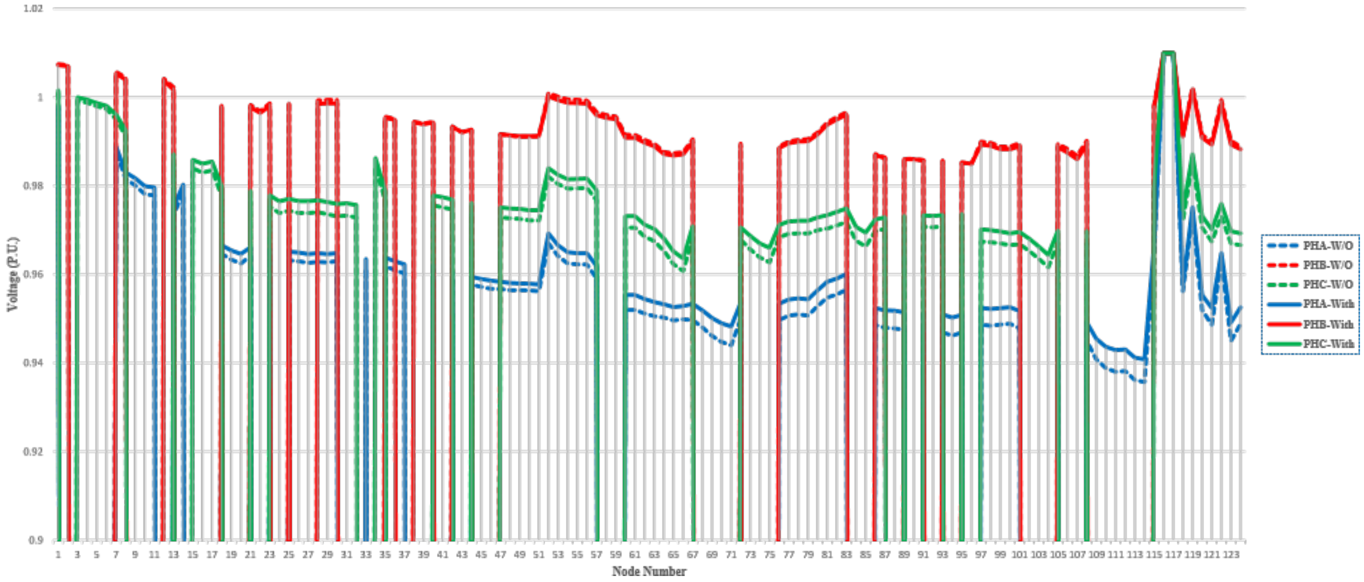

Figure 10. The voltage at different nodes before and after implementing the strategy.

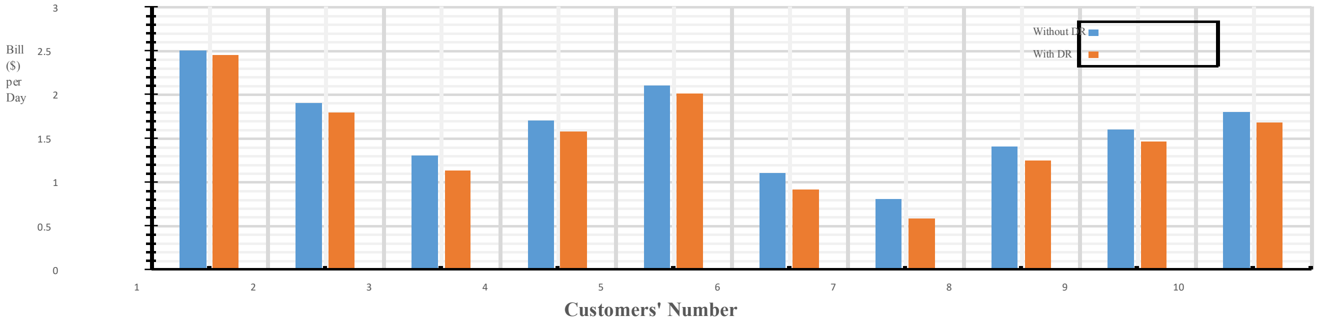

Figure 11. Daily electricity bill for customers 1–10 in node 83 with and without DR program.

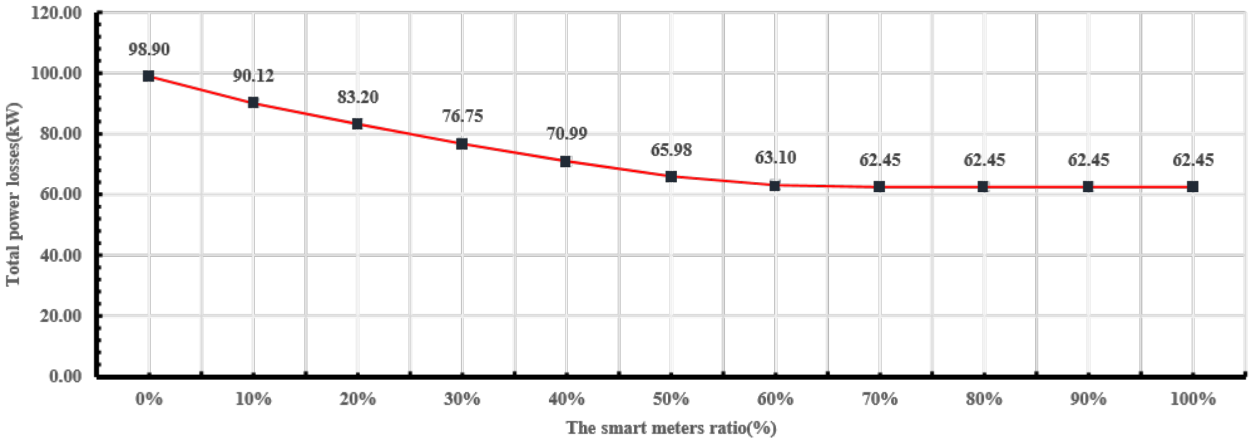

Figure 12. Power losses based on the ratio of the number of smart meters to the total number of all meters.

5. Conclusion

In this paper, a novel strategy based on a game theory framework and IoT platform is proposed. The practical usage of the proposed strategy has been discussed. This is a mechanism that sets different prices to different nodes of the smart grid that are calculated based on the net value of the neutral current at each node. The customers at each node cooperate with each other to mitigate the neutral current by optimal re-phasing which should be done at their smart meters. The customers' utility of the proposed DR program is a linear function of the relevant attached node's price. This approach is remarkable due to its simplicity. Actually, all the customers of a specific node play non-cooperative game, because they are being charged at a nodal electricity price depending on the customers' phase assigning. It was proved that the game was in a unique Nash equilibrium and as regards to the fact that the utility function depends on the nodal prices, which is a function of the net value of the neutral current and relied on the phase assignment of customers, playing the game will result in the optimal rephasing. This paper allows customers enough flexibility to communicate consumption data and identity information with the aid of IoT. In real-world, an IoT platform is advised to be granted to customers for easy-implementing of this strategy. The most prominent application of this strategy is in the smart grid. In this case, a novel approach to re-phasing the customers were implemented on a sample grid. Its simulation results verified the efficiency of it in 3-phase load balancing. The approach increased the customers' utility, reduced the phase unbalance, and also improved the power quality state of that case.

As the proposed concept, this article provides new study guidelines to develop more effective re-phasing approach; it can also be enhanced further in future studies by employing a detailed load model.

APPENDIX

N-PERSON GAME-THEORY

Intuitively, it will be presented that the proposed customers' side game firstly has a NE; and secondly, that is unique.

In [33], a proof of the existence of the NE in finite games is presented. In other words, each game with a finite number of players and strategy profiles is subjected to at least one Nash equilibrium. The uniqueness of the game results from [34]. Note that utility function Uj(.) is an affine function and concave. Furthermore, the electricity price at each node is a linear function to the sum of current consumption vectors. Ergo, the utility function of every user is concave. Consequently, the proposed game is a concave N-person Game. Hereon, the NE is unique due to [Theorem 3] of [34].

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