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A Real-Time Optimization of Reactive Power for An Intelligent System Using Genetic Algorithm

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ABSTRACT Power factor (PF) is a measure of how effectively electricity is used. The low power factor causes considerable power losses along the power supply chain. In particular, it overloads the distribution system and increases the power plant's burden to compensate the expected power losses. Most of the existing PF correction techniques are developed based on placing centralized capacitors, assuming that power systems are static. However, the power systems are dynamic systems such that their states change over time, necessitating dynamic correction systems. In the emerging smart grid systems, real-time measurements can easily be taken for voltage, current and harmonics. Then, the measured data can be transmitted to a PF controller to reach the desired PF value. However, the problem that will arise in real-time applications is how to determine and adjust the optimal capacitor size that can balance the power factor. In this regard, we propose a real-time correction system based on multi-step capacitor banks to improve PF in co-operation with de-tuned filters to mitigate the harmonics. First, a mathematical model has been formulated for the proposed power factor correction system. The mathematical model can be employed to determine the optimal operational settings of the multi-step capacitor and the reactor value that optimize the reactive power while considering the desired PF value and restricting the harmonics. Second, a genetic optimization approach is applied to solve the proposed mathematical model as it can provide accurate solution in a short computational time. A Monte Carlo simulation approach is considered for validating the proposed PF correction system. The simulation results show that the average PF of the randomly generated test instances has improved from 0.7 to 0.95 (35% increase). Furthermore, we conducted real experiments using a PF testbed for experimental validation. The results are found to be consistent with the simulation results, which validate the effectiveness and applicability of the proposed correction system. Furthermore, the saved kVA in one day is estimated to be 26% of total kVA.

INDEX TERMS Electric energy, smart grid, dynamic power system, power factor, intelligent system, mathematical modeling, optimization, genetic algorithm, Monte Carlo simulation, testbed.

I. INTRODUCTION

Nowadays, the world efforts are put towards researches related to increasing energy use efficiency and enabling sustainable energy. Moreover, traditional power grids are currently being transformed into smart grids in order to efficiently and effectively manage the supply chain of the electric power. Power factor is a measure of how effectively electricity is used. The electric energy is almost exclusively generated, transmitted and distributed in the form of alternating current. The low power factor is highly undesirable as it causes an increase in current, resulting in additional losses of active power throughout the electric power supply chain [1]. As such, low power factor would result in overloading in distribution system and hence increasing the burden of the generation power plant to compensate the expected losses [2]. Therefore, there is an immense potential to improve the energy efficiency through power factor improvement.

Low power factor is recognized as a major concern in improving energy efficiency and power industry engineers

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are striving actively for commercial and engineering methods for its correction [3]–[5]. Most of the existing correction methods rely on placing centralized capacitor banks near the load centers [6], [7], and [8]. However, there are several issues associated with capacitor banks. Primarily such solution is costly (typically US$100 = kVAr) requires large space to install, and can only supply reactive power but they cannot absorb it [9], and [10]. Moreover, when faced with rapidly increasing load and voltage drop, capacitors become increasingly less effective and can actually contribute to the downward spiral characteristic of voltage collapse. This characteristic makes them poor at coping with voltage instabilities and preventing voltage collapses. Sometimes they explode due to sudden short circuit. Proper containment, fusing, and preventive maintenance can help to minimize these hazards, which can be expensive. In the Egyptian power system, 9635 MVAr capacitors has been installed on the medium and low voltage network and 800 MVAr on the high voltage (220kV) [11]. The typical rate structure of the grid incorporates power factor penalty based on kVAr-hours or kVA demand. Generally, there is a penalty of charge if power factor falls below a certain level. The most benefit to both the utility and the customer occurs when cost of pricing is similar to the cost of service.

Several studies have attempted to address the power factor problem, considering several correction techniques [4]–[8]. Miwa *et al.* [4] introduced a method for automatic power factor correction by embedded system. This method is mostly used in the Switched Reluctance Motor controller drive. Balogh and Redl [5] achieved the power factor correction by using microcontroller with synchronous condenser instead of capacitor bank. In this method, the harmonics are also reduced by synchronous condenser. Grebe [6] used power electronic system for improving the power factor by changing the wave shape of current drawn by a load. The purpose is to make the load circuitry appear purely resistive. Power factor correction using a dynamic voltage restorer is introduced in [7]. In this method, a dynamic voltage restorer is based on a Voltage Source Converter (VSC) scheme for voltage compensation due to the presence of sags of amplitude which is a custom power device used for mitigation of voltage sag and swell where Voltage sag and swell are the major problems in power quality such as harmonic distortion, flicker, notching, transient and low power factor. The power factor correction method of a non-resonant IPT system using a four-winding transformer is discussed in [8]. Cano Ortega *et al.* [12] proposed a real-time power factor correction system that relies upon capacitor banks and teacher learning based optimization algorithm. They formulated an optimization model in which the objective is to minimize the difference between the desired and actual power factor values. However, their optimization model does not account for harmonics. They have tested the proposed PF correction system through a testbed.

Most of the power factor correction techniques are developed assuming static power systems [1], [4]–[8]. However, the power systems are dynamic systems that their states change frequently as different types of loads are switched on and off over time, necessitating dynamic correction systems. This work proposes an intelligent system for power factor correction in real-time using multi-step capacitor with multi stage reactor which is used to mitigate harmonics and protect the capacitor from overvoltage. In the context of smart grids, real-time measurements can easily be taken for voltage, current and harmonics. Then, they can be transmitted to a PF controller to reach a desired PF value. However, the problem that may arise in real-time applications is how to determine and tune the optimal capacitor size that can balance the power factor. In this regard, we propose a real-time correction system based on multi-step capacitor banks to improve PF in co-operation with de-tuned filters to mitigate the harmonics. The optimal capacitor size should be determined in a very short computational time as per real-time applications. Therefore, a mathematical model is formulated to describe the proposed PF correction system. The proposed model can be employed to determine the best operational settings of the multi-step capacitor and the reactor value that optimize the reactive power while considering the desired PF value/range, and restricting the harmonics to its acceptable limits. A genetic optimization approach is applied to determine the best operational settings. The genetic algorithm suits real time applications as it can provide accurate solution in a short computational time. In particular, the genetic algorithm is applied to estimate the needed value of the capacitor to improve the power factor and the value of reactor to mitigate harmonics to be lower than 8%, and reactor impedance to be between 4% and 15%.

The effectiveness of the proposed PF correction system has been evaluated through randomly generated test problems, while considering the real load data collected from a selected building at an Egyptian University. In particular, the power system has been simulated for a number of days with partitioning each day into 48 time periods. In each time period, the state of the power system is randomly changed through Monte Carlo simulation and the genetic optimization algorithm is applied to determine the optimal capacitor size that balances the power factor. In the generated problems, the consumed power has been found to vary between 60 kW and 130 kW and power factor varies from 0.56 to 0.83. The results show that the average power factor has improved from 0.70 to 0.95 which validate the effectiveness of the proposed genetic optimization approach. Furthermore, we conducted real experiments using a PF testbed for experimental validation. The experimental results are found to be consistent with the simulation results. Furthermore, the saved kVA in one day is reached to 26% from total kVA.

The key contribution of this paper includes the proposed intelligent system that can be integrated with the emerging smart grid systems to correct the power factor in real-time at distribution side. The validation through both the simulation and the testbed experiments has proved the effectiveness and applicability of the proposed correction approach.

Moreover, a mathematical model that can be employed to optimize the reactive power is presented. The model can be considered another contribution as it may be adopted by other researchers to accommodate other system configurations. Moreover, it can be utilized by other researchers to develop alternative intelligent systems for correcting power factor. Finally, the reported results of both the simulation and real experiments can be considered for benchmarking of future intelligent systems for correcting PF.

The paper is structured as follows. The system description is introduced in Section 2. The mathematical model that can be used to optimize the reactive power is presented in Section 3. The genetic optimization algorithm is exhibited in Section 4. The results are presented and discussed in Section 5, and further discussion and implications are provided in Section 6. The conclusions and future work are summarized in Section 7.

II. SYSTEM DESCRIPTION

Power factor is the cosine of the angle between voltage and current. The phase difference arises from the type of load where the current lags behind the voltage in inductive loads [13]. However, the current leads the voltage in capacitive loads. The ratio of the load reactance detects this phase shift. Low power factor has many drawbacks in AC circuits. It affects transmission line and grid such as:

- Large kVA rating of equipment.
- Higher conductor size: low power factor results in high current.
- Lower voltage regulation due to higher voltage drop across the transmission line.
- Higher power losses.

This leads to the importance for power factor correction. In power distribution systems, there are variable loads that can also be linear and non-linear loads. The power factor varies related to loads, and non-linear loads generate harmonics in the system. Therefore, variable capacitor banks can be used to improve power factor. In addition, variable detuned filter can be integrated with variable capacitor banks to mitigate the harmonics and protect the capacitor from blowing.

Smart grid provides smart meters that can provide the date needed to get optimum capacitor and reactor to minimize THD and reach the desired power factor. The steps of capacitors which are used here are reduced by using steps where each step is double the previous step. This will provide long range of capacitor values as shown in Fig.1 and less number of switching. The rated voltage of the capacitor must be larger than the rated voltage of distribution system to avoid over voltage due to harmonics (about 120%) and reactor connection which will rise the voltage on capacitor to b% (b is the ratio of reactor to the capacitor impedance) is commercially about 7% and could be reached to 14% if the system is rich with 3rd harmonics. In this case the system needed to mitigate harmonics to will be less than 6%. In this case, it must take

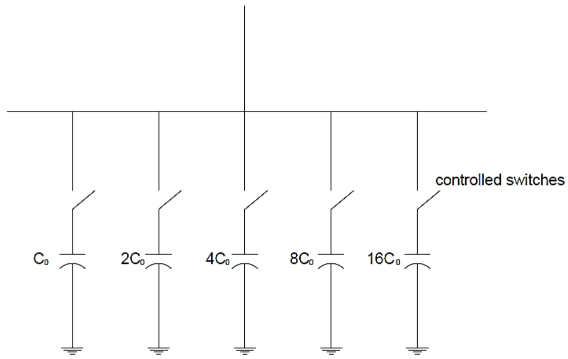

FIGURE 1. Steps of the capacitor bank.

care with current harmonics because it may cause system resonance and premature capacitor and reactor failure.

III. MATHEMATICAL MODEL FORMULATION

This section presents the mathematical model that governs the power factor in the presence of multi-step capacitors. The mathematical model can then be formulated as an optimization model that can be relied upon to optimize the reactive power and adjust the power factor in real-time while considering the system's constraints.

In the context of smart grids, real-time measurement can be taken for voltage, current and harmonics. Then, the collected data are transmitted to a controller in order to analyze the data and get a reaction to reach a desired power factor. In this regard, real-time power factor must be calculated by the controller from input signals by calculating the phase shift between current and voltage by op-amp as shown below:

$$PF = \cos(\varphi) \tag{1}$$

where φ is the angle of the power factor in degree and is defined by the angle difference between the voltage signal and the current signal.

Then, the reactive power Qc needed to reach the desired power factor can be calculated as follows:

$$Q_C = P \times (\tan(\varphi_{new}) - \tan(\varphi_{old})) \tag{2}$$

where Q_C is the reactive power in VAr, P is the active power in watt, φ_{old} is the angle of uncorrected power factor in degree, and φ_{new} is the angle of the corrected power factor in degree [14]. Accordingly, the required capacitor value C to achieve the new power factor can be calculated as follows:

$$C = \frac{Q_C}{V^2 \times \omega} \tag{3}$$

$$\omega = 2\pi f \tag{4}$$

where C is the capacitance in Farads, ω is the angular velocity in radians per second calculated for the fundamental frequency, and V is the voltage in volt.

The total harmonic distortion (THD) should be controlled so that the resonance and any harmful effects on the capacitor can be avoided. The total harmonic distortion (THD) can be

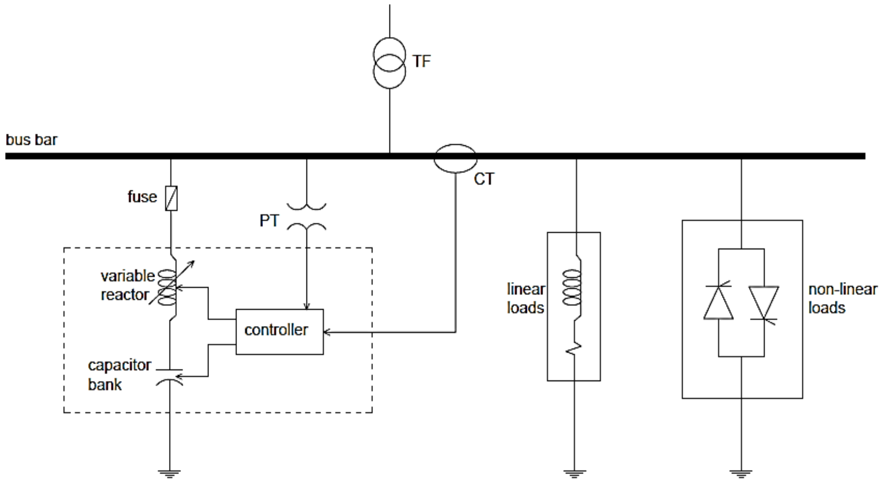

FIGURE 2. Single line diagram of the construction of the distribution system.

expressed mathematically as follows:

$$THD = \frac{\sqrt{\sum_{n=2}^{n=\infty} V_n^2}}{V_1} \tag{5}$$

where n is the order of the harmonic, V_n is the voltage of the nth harmonic, and V_1 is the voltage of the fundamental frequency [15]–[18]. The voltage of the nth harmonic can be calculated as follows:

$$V_n = I_n \times Z_n \tag{6}$$

where I_n is the current of the nth harmonic in ampere, and Z_n is the equivalent impedance of the circuit shown in Fig. 2 in ohm which can be calculated as follows:

$$Z_n = \frac{n \times X_{tr} \left(n^2 \times X_r - X_C\right)}{n^2 \left(X_{tr} + X_r\right) - X_C} \tag{7}$$

$$X_{tr} = j \times \omega \times L_{tr} \tag{8}$$

$$X_c = \frac{1}{j \times \omega \times C} \tag{9}$$

$$X_r = X_C \times {}^{b}/_{100} \tag{10}$$

where X_C, X_r, and X_{tr} are the reactance of the capacitors, reactor, and transformer respectively in ohm, that are calculated for the fundamental frequency; and b represents the percentage of the impedance of the reactor of de-tuned filter to the total impedance of capacitor.

The multi-step capacitor consists of m steps that each step k $(k = 1, \ldots, m)$ has a capacitor value C_m. The multi-step capacitor can be adapted every time a corrective action is needed to adjust the measured power factor to a desired value. This can be realized by turning on/off the number of capacitor steps that produce the total capacitor value C required to correct the power factor. This can be represented mathematically as follows:

$$C = \sum_{k=1}^{k=m} C_k \times S_k \tag{11}$$

where S_k represents the state of each step k of the multi-step capacitor such that $S_k = 1$ means that the step k is turned on, and $S_k = 0$ when the step k is turned off. In real-time correction of the power factor, it will be required to determine the state of each step so that the total capacitor value C is sufficient to correct the power factor. The construction of the distribution system is depicted in Fig. 2 with capacitor bank and de-tuned filter. Multi-step capacitor bank, built as shown in Fig. 1, is switched with having THD is lower than or equal to 8% according to standard IEEE-18 and having the reactor of de-tuned filter to be within 4% and 15 % of total impedance of capacitor [19].

Ortega [12] has proposed a mathematical model that can be employed to compensate the power factor through determining the appropriate capacitor size. In their model, the objective function is the difference between the old and new power factor values. We consider a different formulation for the problem in which the objective is to minimize the reactive power while considering the desired power factor as a constraint such that lower and upper bounds can be set for the desired PF value. The bounds on the desired PF value can be determined by the grid and to be used as an input to the model. Furthermore, we consider the total harmonic distortion as a constraint such that the model will produce compensation solutions that achieve the desired PF value while restricting the value of THD to be lower than or equal to 8%. The complete optimization model that can be used to optimize the reactive power and compensate the power factor is formulated as shown below:

Objective function

$$Min\ F = \left| P \times \left(tan(\varphi_{old}) - tan(\varphi_{new})\right) + (V^2 \times \omega \times \sum_{k=1}^{k=m} C_k \times S_k) \right| \tag{12}$$

Subject to

$$THD \leq 8\% \tag{13}$$

S_1	S_2	....	S_{k-1}	S_k	b

FIGURE 3. The structure of a chromosome.

$$4 \leq b \leq 15 \tag{14}$$
$$PF_{new}^{L} \leq PF_{new} \leq PF_{new}^{U} \tag{15}$$
$$S_k \in \{0, 1\} \tag{16}$$

The sets of decision variables of this optimization model include the state of the steps of the multi-step capacitor S_k, and reactor value b. The objective function (eq. (12) minimizes the difference between the new reactive power and the old reactive power plus reactive power of the added capacitors. The first constraint is related to the total harmonic distortion that should not exceed 8% (eq. (13)). The second constraint represents the allowable range of the reactor of the de-tuned filter that should be within 4% and 15 % of total impedance of capacitor. The third constraint (eq. (15)) ensures that the new power factor is within the acceptable range where PF_{new}^{L} and PF_{new}^{U} are the lower and upper limits of the desired power factor. The last constraint defines S_k as a binary decision variable.

IV. OPTIMIZATION ALGORITHM

The presented mathematical model for governing the power factor through multi-step capacitors in real-time is new. As such, there are no previously recommended optimization algorithms for dealing with this optimization problem. The genetic algorithm (GA) is one of the common meta-heuristic optimization techniques that can address real-time optimization problems such as the PF correction problem addressed in this research. GA has shown a promising performance in real-time optimization of different power system problems [20], [21]. It also suits the optimization problems that include binary decision variables. Therefore, the genetic algorithm is chosen and applied to solve the above-described optimization model for the power factor problem. Genetic algorithms are based on the principles of natural genetics and natural selection. The basic elements of natural genetics; reproduction, crossover and mutation are used in the genetic search procedure [22], [23]. Each chromosome has solution values of capacitor and reactor as shown in Fig. 3.

The flowchart in Fig.4 shows the proposed genetic algorithm for power factor correction. In every time period, the current and voltage sensors measure the signal of current and voltage and power quality meter measures harmonics. Then, the PF is calculated and if it is greater than or equal to the desired one, no actions are needed and the capacitor state is remained unchanged. Otherwise, GA starts generating chromosomes for the decision variables S_k and b where each chromosome consists of $k + 1$ genes with the first k genes representing the k steps of the multi-step capacitor and the last gene represents the reactor value b. The GA starts by generating randomly a population of chromosomes where the size of the population can be set before running the

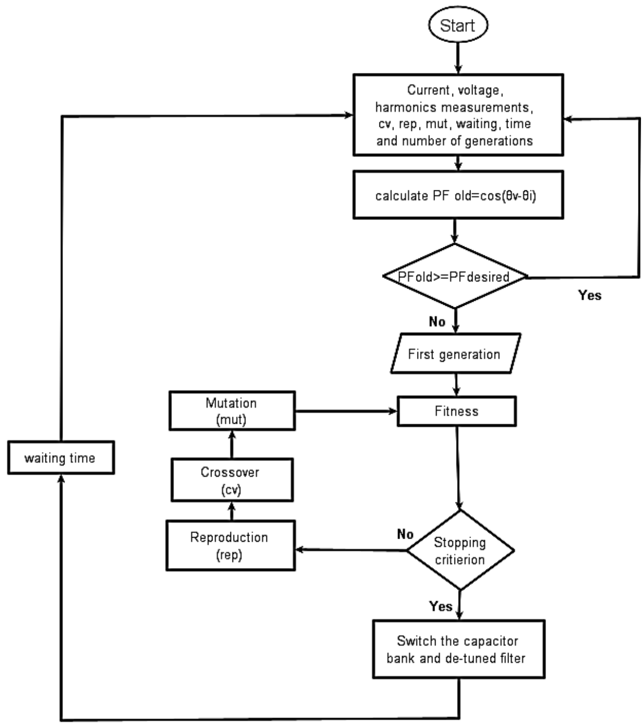

FIGURE 4. The flowchart of the optimization algorithm.

algorithm. Then, the fitness function is evaluated for all the generated solutions as well as the model's constraints and if some solutions satisfy the constraints and the stopping criteria, the algorithm terminates and transmits the obtained solution to the controller to turn on/off the respective steps of the multi-step capacitor.

Otherwise, a new population is obtained from parents selected in the previous generation. The regeneration process includes reproduction, crossover and mutation that can be controlled with the parameters cv, rep, and mut, respectively. The reproduction represents the selection of some of the chromosomes that have the highest fitness values. The crossover selects some chromosomes and combines them to create a new set of chromosomes where the encoding method defines the crossover method. Mutation takes place after reproduction and crossover are performed as it is used to prevent falling at local optimum. This represents the steps of a complete iteration while searching for the optimal solution. The algorithm repeats these steps until it finds the solution that satisfies the stopping criteria. Finally, the controller takes action to switching the capacitor bank and the de-tuned filter. The correction system is resumed after a time interval (waiting time) to measure and correct the power factor continuously.

V. RESULTS ANALYSIS

The validation of the proposed PF correction system has been conducted through both simulation and real experiments. The Monte Carlo simulation approach is used to randomly generate test problems to assess the effectiveness of the proposed PF correction system. The real experiments are performed based on a testbed that was developed in the lab for the validation purpose of the proposed system.

A. VALIDATION THROUGH SIMULATION

The proposed optimization algorithm has been validated through randomly generated test problems, while considering the real load data collected from a selected building at an Egyptian University. In particular, the power system has been simulated over 48 time periods in a day, assuming that the system state changes every 30 minutes. At the beginning of each time period, the state of the power system is changed through Monte Carlo simulation by randomly turning on/off the building loads [24]. The genetic optimization algorithm is implemented to determine the optimal capacitor size that balances the power factor in each period.

In the generated test problems, the consumed power varies from 60 kW to 130 kW and the power factor varies from 0.56 to 0.83. The target is to reach to a power factor of 0.95 while restricting the harmonics. The data of capacitor is designed related to IEEE-18 standards and to be placed at main distribution board [19]. The GA will control the switching of the capacitor bank with real-time data. The load profile is generated by Monte Carlo simulation, with the following assumptions:

a- The designed capacitor bank is suitable for the variation of the load.
b- *THD* should be in compliance with standards.
c- The calculations are obtained for the case which is limited to the economic power factor and not maximize power factor to 1.0 [13].
d- The real-time data of voltage, current and harmonics are available.

In the simulation runs, the parameters of the GA are considered as follows:

- Population size: 100
- Selection operator: Roulette
- Mutation operator: Adaptive feasible
- Crossover operator: Two point
- Probability of crossover: 0.6
- Probability of reproduction: 0.3
- Probability of Mutation: 0.01
- Probability of elite: 0.1
- Stopping criteria: Stall (60 generations)

The Monte Carlo simulation approach has been used to simulate the load profile for five days. Each day is partitioned into 48 time periods of 30 minutes each. The number and types of loads are randomly switched on/off every 30 minutes, resulting in a different PF that should be corrected to reach a desired PF value, while considering the *THD* and *b* limits. Thus, it is assumed that the system state is static within each time period. The simulation has been implemented in Matlab.

The simulated load profile for a given day (with and without capacitor bank) is shown in Fig. 5. The figure shows that the reduction of reactive power which will improve the power system reliability by reduction of kVA consumed of

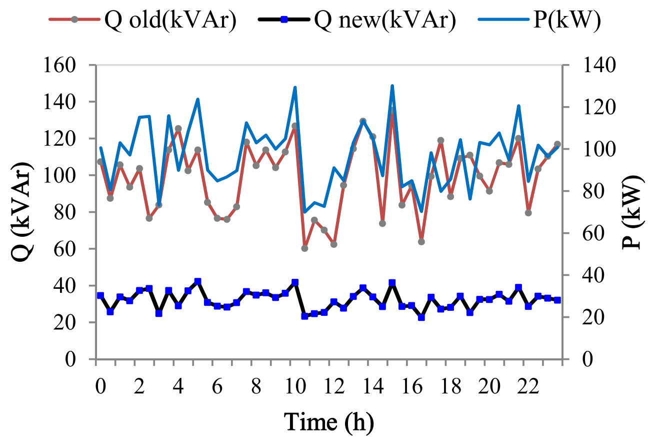

FIGURE 5. Load profile with and without capacitor bank.

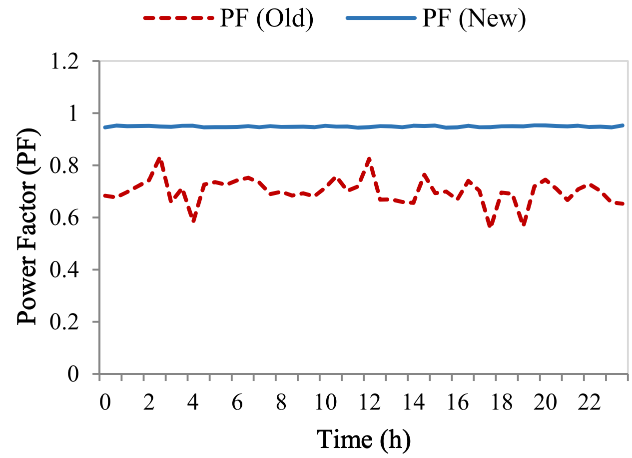

FIGURE 6. Power factor with and without capacitor bank.

the power system. The related power factor is improved and almost fixed at the desired value (see Fig. 6). Furthermore, Fig.7 shows the reduction of kVA that will reduce the installation equipment, cables for utility grid and penalty cost of low power factor for customer. The saved kVA in one day has reached to 26% of total kVA.

The simulation results of the five days are presented and summarized in Table 1. The results include the average measured power factor and its standard deviation, and compared to the corrected power factor that resulted after implementing the genetic optimization approach. The average measured power factor ranges from 0.6457 to 0.7259, with a standard deviation that ranges from 0.01 to 0.0514. The grand average of the measured power factor is 0.701. The results show that the average power factor has improved in all the five simulation runs. In particular, the optimized power factor ranges from 0.9489 to 0.9499, with a grand average of 0.95. As such, the average power factor has improved from 0.701 to 0.950 with an increase of 35%. Furthermore, the standard deviation has improved considerably with a 90% decrease. The computational time is a fraction of second in all cases, implying a very short computational time which is suitable

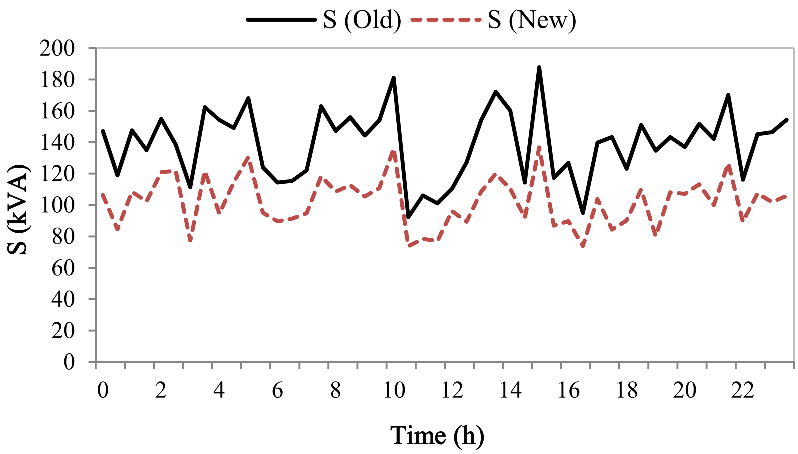

FIGURE 7. kVA before and after power factor correction.

TABLE 1. Average power and power factor for five days with and without capacitor bank.

Simulation Run (Day)	P (kW)	Measured Power Factor (Without Multi-step Capacitor)		Optimized Power Factor (With Multi-step Capacitor)	
	Average	Average	Standard Deviation	Average	Standard Deviation
1	96.9857	0.7003	0.0514	0.9489	0.0026
2	130.343	0.7257	0.0126	0.9499	0.0021
3	104.622	0.6457	0.0113	0.9498	0.0026
4	147.167	0.7259	0.0100	0.9499	0.0019
5	98.2182	0.7092	0.0300	0.9499	0.0027
Average	115.467	0.701	0.023	0.950	0.002

for real-time applications. The simulation results prove the effectiveness of the proposed optimization approach to correct the power factor in real-time.

B. VALIDATION THROUGH TESTBED EXPERIMENTS

In order to verify the results obtained by the simulation model, a testbed was built in the laboratory to validate the proposed PF correction system (see Fig. 8-9). Fig. 9 illustrates the power factor testbed that has been made in the lab. The testbed consists of a control station, Wi-Fi infrastructure and smart meter with power factor correction capabilities. The smart meter gets their power factor correction parameter setting from the control station and runs the proposed algorithm, takes decision and sends it to the multi-step capacitor bank and the detuned filter. The testbed controls the load for a wide range of PF values. For example, it has coils (label 1) with different inductance in order to simulate various inductive loads and hence allowing a wide range of power factor values. The inductive loads are controlled with push button (label 8) with LED indicators (label 7). In addition, sockets (label 2) are used to add resistive/inductive loads to control the value of the load PF. The Wi-Fi module (label 3) is used to communicate with the control unit (workstation). The testbed has a smart meter (label 4) that used to measure the power line PF and active/reactive power. It is powered by the power line as shown (label 9). Furthermore, the testbed contains a multi-step capacitor bank (label 5) with detuned filter (label 10). In addition, the testbed has relays (label 6) to control the capacitor bank and detuned filter.

We have conducted the experiments with the power factor testbed with different load current and PF as indicated in Table 2. The range of the desired power factor in the experiments is set to $0.92 \leq PF_{new} \leq 0.95$. The second and third columns, in Table 2, represent the active and reactive power of the loads, respectively. We used loads with different power consumption 138 Watts to 421 Watts. The fourth and fifth column represent the current and the PF of the corresponding load before power factor correction. The load PF ranges from 0.38 to 0.59. The sixth and seventh column contains the current PF values and the new PF values after applying

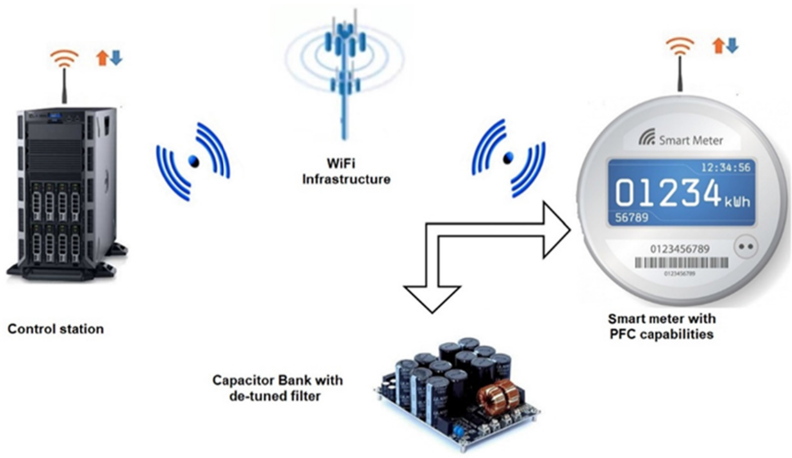

FIGURE 8. Schematic diagram for the power factor correction system in the smart grid.

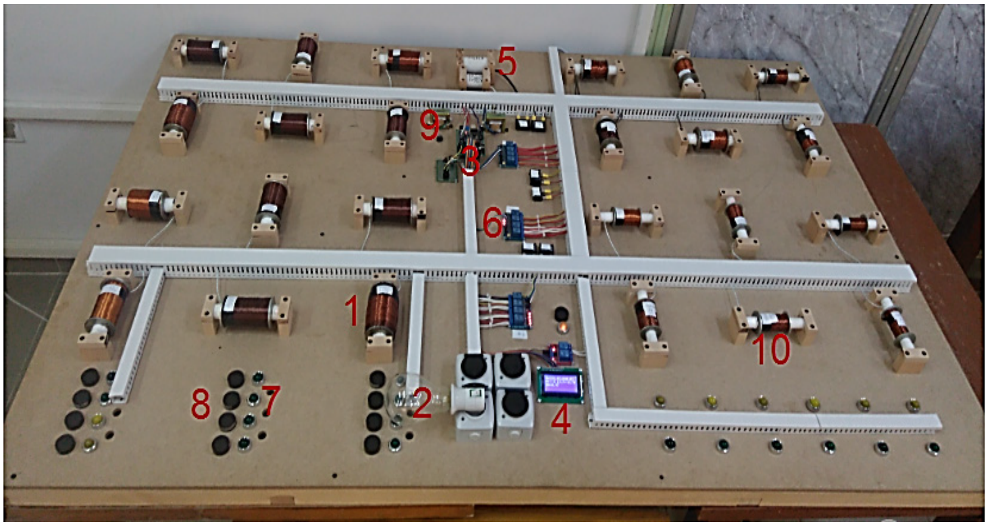

FIGURE 9. Power factor correction testbed done in the laboratory.

TABLE 2. Results of power factor experiments.

Experiment No.	Load		Without the capacitor bank		With the capacitor bank	
	Real power (W)	Inductive reactive power (VAr)	Current (A)	PF	Current (A)	PF
1	138	209.60	1.10	0.55	0.67	0.93
2	149	258.10	1.30	0.5	0.70	0.94
3	178	373.70	1.77	0.43	0.81	0.94
4	205	499.00	2.33	0.38	0.98	0.94
5	421	576.10	3.16	0.59	2.00	0.92

the proposed algorithm. The current decreased dramatically in all cases. For example, it goes from 2.33 Ampere down to 0.98 Ampere in the experiment no. 4. In addition, the PF increases in all cases to a value greater than or equal to 0.92. For example, it becomes 0.93 in the experiment no. 1.

The experiment shows that the proposed PF correction system runs reliably over a range of the load/PF. As the load PF is increased, the associated load current is reduced. This will reduce the losses associated with high current in the cables.

VI. CONCLUSION

Low power factor is recognized as a major concern for improving energy efficiency and power industry engineers are striving actively for a commercial and engineering method for its correction. Most of the existing correction approaches concentrate on improving power factor by placing centralized capacitor banks near the load centers. However, such methods are developed based on the assumption that power systems are static. Nevertheless, the power system state changes frequently as different types of loads are switched on and off overtime, requiring the need for dynamic correction systems. This paper proposes an intelligent real-time correction system based on multi-step capacitor banks. It can improve power factor in real-time using multi-step capacitor while considering the operational constraints. A genetic optimization approach is employed to determine the best capacitor size that optimizes the reactive power and adjusts the power factor without violating the system constraints. The simulation results show that the average power factor has improved from 0.701 to 0.95 (35% increase) which validate the effectiveness of the proposed genetic optimization approach. Furthermore, the real experiments based on the testbed have confirmed the effectiveness of the proposed power factor correction system. kVA reduction is reached to 26% from total kVA. This will improve power reliability and increase system capacity.

This paper has introduced a novel intelligent system that can be adopted by electricity distribution companies to improve the performance of the grid. Up to our knowledge, this is the first attempt to introduce such correction system that suits real-time applications. In particular, the proposed system can be easily integrated with smart grids to improve energy efficiency at distribution side. Furthermore, the results presented in this paper can be used for benchmarking future real-time corrections systems since the published results related to this problem are rare.

The future work can be extended in different direction. We have formulated the mathematical model that can be used to optimize the reactive power based on multi-step capacitor banks. We have selected the genetic algorithm to solve this model. As such, future research could consider the formulated mathematical model and evaluate other optimization techniques to solve it. In particular, the accurate and fast solutions are important criteria in evaluating the different optimization approaches for this problem. The mathematical model can be adapted to accommodate other system configurations.

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