Interactive Power Factor Management with Incentives Towards Reduction in Fuel Consumption and Carbon Emission

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ABSTRACT Reducing costs and emissions, and improving efficiency in the electric power networks are becoming urgent. It is, therefore, necessary to apply improvements in the industry’s operation. A case in point is the current efforts to maintain acceptable consumer’s operational PF (PFOpr) gauged against reference PF (PFref), where the penalties are levied on monthly averaged PFOpr below PFref. The efforts can be enhanced if based on interactive involvement and participation between consumers and services providers (SP’s), mainly by the fair implementation of penalties and incentives. Enticing consumer participation enables mutual benefits. The current treatment of PF in Saudi Arabia is based on average monthly measurements of consumers’ PFOpr over an extended period. In this spirit, a novel mathematical model and framework are presented which consist of a time-referenced function relating applicable tariff to PFOpr, thus benefiting the SPs by reducing the capital and maintenance costs, providing flexibility to focus on the peak load periods, and rewarding incentives to the consumers maintaining PF in an acceptable range. The model was implemented on energy measurements at four industrial facilities for one year and the results were verified in terms of reduction in losses, and the resulting monetary benefits, and reduction in CO2 emissions.

INDEX TERMS Energy management, energy measurement, load management, power factor, power system economics, tariffs.

I. INTRODUCTION

LOW PF implies reduced operating efficiency which results in a need for larger conductors (wires) and increased equipment capacity, as well as causing voltage drops as power losses increase. These equate to higher capital investments and expenses and lower system performance. PF correction contributes to energy saving in general which can be directly correlated to PF difference, and how heavily loaded inductive devices are in the distribution system. However, correcting PF can bring significant savings in energy bills if the utility imposes a low PF penalty in their rate structure, as most utilities do for industrial consumers [1]–[3].

Most of the international utilities consider specified fees for lower PFOpr with respect to PFref. An extensive review of the literature [4]–[9] indicates, that most of the utilities impose penalties for low PFOpr viz a viz assigned PFref, with varying qualifications for the connected kVA, kWh consumption, and range of deviation below PFref. Consumers with averaged PFOpr below reference PFref are charged a fixed amount per unit of reactive energy. In some cases, energy tariffs have a multiplier or an adjustment for low PFOpr. In others, a minimum PFref level is set for penalty and threshold for energy consumptions (kWh). In this study, an investigation for alternative billing methodology based on the stated reference [1], using dynamic measurement of PF is proposed and analyzed.

In the literature, Austin Energy tariff policy indicates that the customers with a high PF (over 90%) consume energy more effectively and, as a result, have a lower cost to serve.
Those with a PF of less than 90% will see an adjustment to the demand kW on which they are billed. The adjustment is calculated based on a formula considering the level and duration of PF utilization [4]. For Duquesne Light Company (DLC), the policy indicates that if a customer is not using the available electricity efficiently, the higher cost is imposed by PF multiplier adjustment [5]. For Oncor Electric Delivery Company (ONCOR), the tariff policy states that if the PF of a retail customer is found less than 95% lagging, it may require the consumer to install appropriate equipment for PF correction. If they fail to correct the PF consistent with this standard, the demand associated with their use of delivery service, as determined in the appropriate rate schedules, may be increased according to the formulas in [6]. The tariff, related to the PF section of British Columbia Hydro states that, if the customer’s average PF for the billing period falls below 90%, the bill will increase by a certain percentage applied to the total of all other charges for the same period [7]. The Egyptian utilities provide bonuses or rewards to the customers for maintaining a high PFopr in the range of 0.92 to 0.95 registered at the end of the year [8].

The Electric Power Research Institute (EPRI) conducted a study [9] entitled, Assessment of Transmission and Distribution Losses in New York State for the New York State Energy Research and Development Authority (NYSERDA), Albany, NY. The study required New York state utilities to identify measures to reduce system losses and/or optimize system operations. They also included the effect of the electric power tariff on the losses. Allegheny Power in the Midwest and Mid-Atlantic regions, US, applied a kVAR charge to the customer’s kVAR capacity which required more than 25% of their kilowatt capacity. While PEPCO, DC, and Maryland, USA do not charge the customers for reactive demand apparently, except for time-metered rapid transit service accounts. The monthly billing reactive demand is the maximum 30-minute integrated coincident kVAR demand of each delivery point served less the kVAR, supplied for an 85% PF. For Georgia Power, if there is an indication of PF less than 95% lagging, the company may, at its option, install metering equipment to measure the reactive demand, which shall be the highest 30-minute kVAR measured during the month. The excess reactive demand shall be kVAR which is over one-third of the measured actual kW in the current month. The company will bill excess kVAR at the rate of USD 0.27 (per kVAR).

In Saudi Arabia, the Saudi Electricity Company (SEC), based on the Water and Energy Regulatory Authority’s (WERA) decision [10] for non-household consumption, charges PFopr below 0.9 with connected load above one MVA and is in the process to increase it to 0.95, with the same connected load. A penalty charge of SAR 0.05 (USD 1 = SAR 3.75) is applied for every additional kVARh registered monthly exceeding 48.4% of the registered active energy consumption corresponding to PFopr 0.9 [10]. Thus, the treatment of PF currently adapted is based on the average monthly measurement of the consumer’s PFopr with a progressive penalty applied for PFopr lower than the PFref. This local and international treatment for low PFref should be adjusted to correct two major shortcomings:

- The monthly average measurement gives misleading information, as it does not allow for a focus on a critical period, i.e., peak load,
- While in some cases [8], [11], flat numerical credit is awarded for improvements in the monthly average PF, it still cannot provide progressive incentives to the consumers, which in turn does not encourage them for promoting further improvements in PFopr, even at a relatively higher marginal investment cost, all subject to its cost/benefit analysis.

In this spirit, a practical and flexible framework of tariff, with incentive and penalty is proposed, with a protocol to rectify these shortcomings. Moreover, an estimate of the monetary values related to the variation in the fuel consumption and CO2 emissions associated with the changes in PFopr has been investigated. The paper is organized as follows. Section 2 builds the background by giving the basis of the mathematical model, citing the current scenario of transmission and distribution losses in the Saudi Arabian context, fuel consumption for energy generation and resulting CO2 emissions, and lastly, the relationship of change in PF with the losses. Based on this background, Section 3 presents the proposed unified framework for incentive-penalty based tariff, a stepwise guide for its implementation, and a comparison of the proposed framework with that of the currently implemented tariff using the energy data of four major industrial entities, collected for a period of one year.

II. BACKGROUND

The presented approach is based on the concept proposed by Zedan et. al. [1], which links PF with the applicable tariff in (1), to provide a mathematical relation giving consumption charge resultant tariff \( T_{res} \) as a function of PFopr registered over timescale (minutes), thereby providing continuous-time referenced action/operation.

\[
\frac{T_{res}}{T} = \left\{ N + (1 - N) \times \left( \frac{PF_{ref}}{P} \frac{F_{opr}}{PF} \right) \right\},
\]

where, \( T_{res} \) is the resulting variable consumption charge tariff in SAR/kWh, \( T \) is the fixed assigned tariff in SAR/kWh, \( N \) is the variable factor (0 \( \leq N \leq 1 \)), \( PF_{ref} \) is the assigned reference PF, and \( PF_{opr} \) is the operational PF incurred by the consumer.

With the advent of digital meters, the proposed model empowers the regulators/SPs to implement a framework for penalties and incentives, tailored to consumers’ operations. Additionally, like time-of-day use, the focus can be placed on critical periods (e.g., peak load).

Equation (1) can be written for consumer’s real energy W (kWh), and apparent energy S (kVArh) as:

\[
T_{res} \times W = T \times N \times W + T \times (1 - N) \times (W / PF_{opr}) \times PF_{ref},
\]

(2)
which can be interpreted as, consumption charge = charge on real energy and drawn apparent energy times $PF_{\text{ref}}$.

With available smart meters, the model in (1) allows time-related gradual penalty or incentive for $PF_{\text{opr}}$ lower or higher than $PF_{\text{ref}}$, respectively. Since $T_{\text{res}}$ is inversely related to $PF_{\text{opr}}$, penalty or incentive increases/decreases with variation in $PF_{\text{opr}}$, an advantage is provided by allowing a gradual increase/decrease in $T_{\text{res}}$ per (kVARh), rather than what is currently applied, i.e., a constant penalty or reward irrespective of the degree of deviation in $PF_{\text{ref}}$. Furthermore, the value of $N$ can be assigned (tailored) to fairly fit the operational practice of each category of consumers.

The correct adjustment of $N$ in (1) provides the means to not only levy penalties but to advance fair and acceptable incentives that encourage consumers to exert efforts and carry the additional investments to maintain a high $PF_{\text{opr}}$. Furthermore, it has been shown in this paper that the segregation of $N$, as $N_{p}$ for the penalty, and $N_{i}$ for incentive, provides independent assignments of the protocol. Depending on the consumption pattern of the category of consumers, a higher value of $N$ provides higher emphasis on the kWh and consequently lower emphasis on kVAh. The paper presents a reliable basis for a narrow range of $N$’s for each category of consumers concerning the changes made in respective $PF_{\text{opr}}$, with resulting positive/negative effects. Furthermore, it presents calculations for the associated monetary values in terms of changes resulting in heat losses, fuel consumption, and CO2 emissions. To establish a reliable base for the approach, and since the instantaneous variation in $PF_{\text{opr}}$ is inversely proportional to the drawn current (I), the resulting current-related heat losses are chosen as the best tool to quantify corresponding positive/negative effects.

A. TRANSMISSION AND DISTRIBUTION LOSSES

Part of the generated energy to serve consumers is dissipated as heat loss across the network. The quantifiable portion thereof is the current related T & D losses. In Saudi Arabia, as per Water Electricity Regulatory Authority’s (WERA) 2018 report [12], 9.5% of the generated electricity is dissipated yearly as losses in the Saudi network. The report also showed that the delivered yearly energy to consumers is 299,188 GWh. Based on this data, it is possible to calculate the generated electricity as 330,594.48 GWh and losses that account for 31,406.48 GWh. These losses are classified into two categories, technical and non-technical. The former is due to the energy dissipated in the conductors, T & D lines equipment, and magnetic losses in transformers, while the latter is due to error in the meter reading, billing of consumer energy consumption, lack of administration, and financial constraints, as well as energy thefts.

The technical losses depend on both the mode of operation and the network characteristics, which can be classified into fixed losses, which are not affected by drawn current such as corona losses, leakage current losses, dielectric losses, and the variable losses, which are proportional to the square of the current. In this study, an evaluation of the effect of improving PF on transmission-connected industries is done by considering only the variable technical losses.

International standards and utility experiences indicate that 30% of the T & D losses are attributed to transmission Ohmic or current related losses [13], [14]. Based on this number, transmission Ohmic losses in Saudi Arabia are calculated as 9,421.94 GWh (30% of 31,406.48) a year. In addition, the ratio of transmission Ohmic losses to sold energy is given as 3.149%, which implies that to deliver 100 GWh to a load, 3.149 GWh is lost in the transmission system as Ohmic losses.

To depict the above losses in terms of the required thermal energy (BTUs), to be followed by resulting CO2 emissions, the following calculations are adopted based on WERA report data [12]. The yearly consumption of fuel for electricity, desalination, and steam production in Saudi Arabia is 3897 MMBTUs; out of this, the consumption for electricity generation is 87% (3390.39 MMBTUs). The portion of different fuel types used for electricity generation is 57% using Natural Gas (NG), 22% using Heavy Fuel Oil (HFO), 18% using Crude Oil (CO), and 3% using Diesel.

B. FUEL CONSUMPTION

To find the number of input thermal energy in BTUs for electric energy generation of unit GWh, we note that the total electrical energy generated from 3390.39 MMBTUs is 330594.48 GWh at the sending end. This results in calculating the amount of thermal energy of fuel used [MBTU] for each produced electric energy in [GWh] as 10255.43 MBTU/GWh. Using this relationship, the energy lost in the Saudi transmission network (transmission losses) is 9,421.94 GWh x 10255.43 MBTU/GWh = 96.63 MMBTUs.

Table 1 shows energy generation by source in GWh for Saudi Arabia [15], where a significant increase in Natural Gas consumption can be seen compared with oil for the nearly same amount of energy generated.

| Year/Energy source | Oil   | Natural Gas | Solar PV | Total  |
|-------------------|-------|-------------|---------|--------|
| 2017              | 173,677 | 204,462     | 155     | 378,294|
| 2018              | 159,528 | 218,470     | 155     | 378,153|
| Percentage change | -8.2  | 6.9         | 0       | -0.04  |

C. CO2 EMISSION

Around 40% of the total CO2 emissions in Saudi Arabia are attributed to the energy sector, followed by industrial processes and agricultural sectors [15]. Currently, the Kingdom is making significant efforts and investments, as well as policy measures to reduce mainly these emissions in line with Article 12.1(b) of the United Nations Framework Convention on Climate Change (UNFCCC), by modernization of the power sector, the establishment of economic cities, investment in infrastructure, and the development and use of renewable energy and gas, to name a few [16].
Implementing PF improvement strategies in the industrial sector, which accounts for approximately 18% of the total electrical consumption as shown in table 2, can result in a significant reduction in CO2 emissions. In the context of the Chinese iron and steel industry, [17] showed that the proposed policies about energy savings and emission reduction could result in a cumulative reduction of 818.3 MtCO2 during the period of 2015-2030, compared with the existing policies.

TABLE 2. Sector-wise CO2 emissions in million-tons [Mt] for KSA [15].

| Year/Sector | Electricity | Other energy industries | Industry | Transport | Residential |
|-------------|-------------|-------------------------|----------|-----------|-------------|
| 2017        | 215         | 29                      | 125      | 143       | 5           |
| 2018        | 195         | 30                      | 125      | 136       | 5           |
| Percentage change | -9.3        | 3.5                     | 0        | -4.9      | 0           |

For Saudi Arabia, as shown in table 2, two major sectors contribute heavily to CO2 production; namely Electricity Heat Producers, and Transport. These two sectors showed a reduction in CO2 emissions of 9% and 5%, respectively, as given in table 2 and figure 1. Other sectors’ emissions remained roughly the same. This can be explained based on switching from Oil to Natural Gas and Solar PV for energy generation because the latter two sources result in significantly less total CO2 emissions. As shown in table 1, there was an 8% decrease in oil consumption, with a similar percentage reduction in CO2 emissions. In the context of energy generation because the latter two sources result in significantly less total CO2 emissions. As shown in table 1, there was an 8% decrease in oil consumption, with a similar percentage reduction in CO2 emissions.

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D. RELATION OF CO2 EMISSIONS TO CRUDE OIL BARREL

The calculation of CO2 emissions per equivalent barrel of crude oil is determined as per the Environmental Protection Agency (EPA). Greenhouse Gases Equivalencies Calculations and References [18], by multiplying the barrel heat content times the carbon coefficient times the fraction oxidized times the ratio of the molecular weight of carbon dioxide to that of carbon (44/12) as follows:

- The average heat content of crude oil is 5.80 mBTU per barrel [18].
- The average carbon coefficient of crude oil is 20.31 kg carbon per mBTU [18].
- The fraction oxidized is assumed to be 100 percent [19]

\[
\frac{5.8 \text{ mBTU}_{\text{barrel}}}{20.31 \text{ kgC}_{\text{mBTU}}} \times \frac{44 \text{ kgCO}_2}{12 \text{ kgC}} \times \frac{1 \text{ mTonsCO}_2}{1000 \text{ kg}} = 0.43 \text{ mTonsCO}_2_{\text{barrel}}
\]

Hence 0.43 metric Tons of CO2 are emitted with the consumption of one equivalent barrel of crude oil.

E. POWER FACTOR AND ENERGY LOSS RELATIONSHIP

In this section, a mathematical relation is presented to relate the variation in PFopr with the resulting percentage variation in heat losses. Assuming a load X utilizes apparent demand (S), and drawn real demand (P) given as,

\[
S = \sqrt{3}VI = \frac{P}{PF}.
\]

Assuming that within a period of PFopr changes, both P, and receiving end voltage V are constant, with drawn current (I), operational PFopr for two cases, PF1 and PF2. Equation (3) gives,

\[
\frac{1}{PF_1} = C_1I_1, \frac{1}{PF_2} = C_1I_2,
\]

where, C1 is a constant equal to \(\sqrt{3}V\). Equation (4) gives,

\[
\frac{PF_2}{PF_1} = \frac{I_2^2}{I_1^2}.
\]

To find the relationship between I, PF, and energy loss (Eloss) for the same time duration, the following analysis is conducted for the two cases:

\[
E_{loss_1} = \sqrt{3}I_1^2Rh = C_2I_1^2, \quad i = 1,2, \quad C_2 = \sqrt{3}Rh,
\]

where R, is the transmission line resistance. Dividing both cases of equation (6) for i = 1, 2, the following is given,

\[
\frac{E_{loss_1}}{E_{loss_2}} = \frac{I_2^2}{I_1^2}.
\]

Equations (5) and (7), provide variation in PFopr as inversely related to the network’s thermal losses, similarly to (BTU) and CO2 emission, and is presented as:

\[
\frac{E_{loss_1} - E_{loss_2}}{E_{loss_1}}
\]

Figure 2 shows the relation between loss difference and PFopr improvement.
Although equation (8) is a quadratic relation, however, within the range of $PF_{opr}$ increasing or decreasing for $PF_{ref}$ by a multiple of $\pm 0.01$, linear approximation gives changes by a multiple of $\pm 2.2\%$, and for an increase of $PF_{opr}$ from 0.9 to 0.95 gives reductions in corresponding heat losses, BTU consumption, and CO2 emission by roughly 11%.

### III. ANALYSIS AND RESULTS

In this section, the benefits of improving $PF_{opr}$ of the industrial sector in terms of reduction in losses are quantified to a certain degree of accuracy. Also, to reflect these savings on the electricity tariff ($T$), a framework is provided for the electricity service provider/regulator, whereby the governing parameters can be chosen to give the desired incentive and penalty for a consumer depending on the changes in $PF_{opr}$.

#### A. ASSESSMENT OF PF IMPROVEMENT

Based on the given background, total savings in terms of equivalent crude oil barrels and CO2 emission mitigation for 1 GWh load are generalized. Table 3 shows the amount of reduction in energy losses in percentage concerning improvements in $PF_{opr}$, given that $PF_{ref} = 0.9$.

It can be seen that if a consumer improves $PF_{opr}$ from 0.7 to 0.9, it will result in a saving of at least 22 barrels and 11 mTons of CO2 for 1 GWh load; these results are also shown graphically in figure 3.

Similarly, if a consumer improves PFopr further above PFref of 0.9, table 4 and figure 4 show the results.

#### B. SELECTION OF INCENTIVE AND PENALTY FOR CONSUMERS

To reflect the savings or additional cost due to a corresponding change in $PF_{opr}$ on electricity tariff, the governing mathematical relationship given in equation (1) is adapted.

For $PF_{opr} > PF_{ref}$, $T_{res} < T$, i.e., incentive. Consequently, for $PF_{opr} < PF_{ref}$, $T_{res} > T$ which enforces a penalty. To arrive at a fair and acceptable range of $T_{res}$ giving reasonable penalty/incentive, the value of $N$ needs to be evaluated based on the proportional sharing savings/losses.

![FIGURE 2. Energy Loss Reduction and PF improvement Relation.](image)

![FIGURE 3. Relationship of $PF_{opr}$ improvements up to 0.9 for 1 GWh load with equivalent crude oil barrels and CO2 emissions in metric Tons.](image)

![FIGURE 4. Relationship of $PF_{opr}$ improvement up to 0.98 for 1 GWh load with equivalent crude oil barrels.](image)
To arrive at the required $N$, the term $(T/T)$ is subtracted on both sides of equation (1), giving,

$$F = \frac{T_{res} - T}{T} = \left\{ N + (1 - N) \times \left( \frac{PF_{ref}}{PF} \right) \right\} - 1.$$  \hfill (9)

Equation (9) gives,

$$F\% = (N - 1) \left( \frac{PF - PF_{ref}}{PF} \right) \times 100.$$  \hfill (10)

To understand the relationship between $N$ and $F$, equation (10) is given with $N = 0$ and $N = 0.99$, which are the minimum and maximum values of $N$, respectively. Following the constraints further, $PF_{ref} = 0.9$, with $PF_{max} = 0.99$ and $PF_{min} = 0.8$ are considered, providing maximum decrease and increase in $T_{res}$, respectively. Defining these limits helps in calculating the boundary values of $F$ as follows,

1) For $N = 0$,
   - $F\%$ at $PF_{max} = 0.99$ will be -9.09%, which gives the maximum incentive.
   - $F\%$ at $PF_{min} = 0.8$ will be 12.5%, which implies maximum penalty.

2) For $N = 0.99$,
   - $F\%$ at $PF_{max} = 0.99$ will be -0.0009%.
   - $F\%$ at $PF_{min} = 0.8$ will be 0.00125%.

These results are shown graphically in figure 5 and table 5.

There are two ways to choose $N$. First, to choose a single value that will fix both the incentive and penalty to corresponding values. The second is to have two different values of $N$, i.e., $N_p$ and $N_f$ to allow the choice of different values of penalty and incentive, respectively.

Figure 5 shows that if it is desired to give a maximum incentive of 5% at user’s $PF_{opr} = 0.99$, then the choice of $N = 0.45$ which also imposes a maximum penalty of approx. 6.5%, if the user operates on the lowest PF of 0.8 – first case for the choice of $N$. For the second case, for instance, $F$ is selected as 5% for maximum incentive and 10% for the maximum penalty, then $N_i = 0.45$ and $N_p = 0.2$, respectively.

### C. PROPOSED METHOD’S IMPLEMENTATION

From the implementation point of view, it is possible to “re-program” the existing energy meters to consider two values of $N$, as described above. This kind of criteria, where the value of a parameter depends on certain operating conditions, is commonly implemented in many electronic appliances. After reprogramming, the meter will keep a check on $PF_{opr}$ and choose the selected values of $N$.

It is worth mentioning that there will be no discontinuity experienced by the energy meter in the calculation of $F$ because of different values of $N$ on both sides of the reference $PF_{ref}$. This is illustrated by the graph in figure 6, which shows that when $PF_{opr}$ switches from penalty to incentive.
TABLE 5. Variation in $F\%$ with respect to $N$, equation (10).

| $N$ | $F\%$ | $F\%$ |
|-----|-------|-------|
| 0   | -9.09 | 12.5  |
| 0.1 | -8.18 | 11.25 |
| 0.2 | -7.27 | 10.0  |
| 0.3 | -6.36 | 8.75  |
| 0.4 | -5.45 | 7.5   |
| 0.5 | -4.53 | 6.25  |
| 0.6 | -3.64 | 5.0   |
| 0.7 | -2.73 | 3.75  |
| 0.8 | -1.82 | 2.5   |
| 0.9 | -0.9 | 1.25  |
| 0.99| 0.09  | 0.13  |

side, there is no discontinuity observed.

FIGURE 6. Effect of two different values of $N$ on $T_{res}$.

In this study, two values of $N$ are used to separately estimate the maximum incentive and penalty. The following steps are outlined to reach the desired value of $N$ using the graph in figure 5.

1) Find the average kWh consumed in a period of one month: $X \text{kWh / month}$,
2)  
   - **PENALTY:** Calculate the share of loss incurred by the consumer as a percentage of total losses in the network: $Y$.
   - **INCENTIVE:** Calculate the share of Ohmic losses incurred by the consumer as a percentage of total losses incurred: $Y$.
3)  
   - **PENALTY:** Divide losses by the total energy consumed to give $F_{p} = Y / X\%$.
   - **INCENTIVE:** Divide the Ohmic losses by the total energy consumed to give $F_{i} = Y / X\%$.
4)  
   Using the graph of figure 5, choose $N_{p}$ or $N_{i}$ according to $F_{p}$ or $F_{i}$, respectively.

The studied sites with available data were analyzed and suitable values of $F_{p}$ or $F_{i}$ were found using the method discussed above and summarized in table 6. The values of $N_{p}$ and $N_{i}$ in the table are the same for all industrial entities studied, which adds to the ease of implementing the methodology.

D. COMPARISON OF THE PROPOSED MODEL WITH CURRENT MODEL IN KINGDOM OF SAUDI ARABIA

In this section, a comparative exercise is conducted using the current practices in Saudi Arabia (WERA Board of Directors’ Decree No. (272/37) dated 21/10/1433 H), which apply a charge on the consumer of SAR 0.05 (USD 0.013) for every additional kVARh below $PF_{ref}$ of 0.9. This implies that consumers at 0.7 and 0.89 $PF_{opr}$ are both affected by the same rate. Figure 7 shows the comparison of resulting penalties and incentives with the proposed approach (called Zedan model in this paper) drawn as a red curve and with current Saudi practice called (WERA model) drawn as a blue curve. In addition, figure 8 shows the comparison of $T_{res}$ with the Zedan model (equation (11)) and that with the current model for industrial tariff (equation (12)).

\[
T_{res} \text{(Zedan model)} = \begin{cases} 
0.18 \left[0.16 + (1 - 0.16) \frac{0.9}{PF} \right] & \text{SAR/kWh : } PF < 0.9 \\
0.18 \left[0.654 + (1 - 0.654) \frac{0.9}{PF} \right] & \text{SAR/kWh : } PF \geq 0.9 
\end{cases}
\]

\[
T_{res} \text{(WERA model)} = \begin{cases} 
0.18 + 0.05(\tan^{-1}(PF) - \tan^{-1}(0.9)) & \text{SAR/kWh : } PF < 0.9 \\
0.18 & \text{SAR/kWh : } PF \geq 0.9 
\end{cases}
\]

FIGURE 7. Comparison of $F\%$ of Zedan model with that of WERA model.

On the penalty side, both figures show that the two models are roughly matched up to $PF_{opr}$ 0.85, while for less than 0.85, the Zedan model charges more penalty rate. This will encourage low $PF_{opr}$ consumers to seek improvement. Furthermore, if it is desired to increase the penalty, $N_{p}$ can be chosen close to zero. On the incentive side, a maximum of 3.5% reduction in $T_{res}$ is seen as an incentive to the consumer with $PF_{opr} = 0.99$ and $N_{i} = 0.654$.

To illustrate the number of potential incentives for consumers of the proposed study, it is noted that all four of them operated on $PF_{opr}$ above 0.9. Table 7 compares the resulting tariff due to the proposed methodology and WERA’s current tariff.
TABLE 6. Choice of $N$ for studied sites in the industrial sector.

| Site | Average Active Energy (kWh/Month) | Shared total losses (kWh/Month) | Shared Ohmic losses (kWh/Month) | Ratio of total losses to energy consumption ($F_p$) | Ratio of Ohmic losses to energy consumption ($F_i$) | $N_p$ | $N_i$ |
|------|----------------------------------|---------------------------------|-------------------------------|----------------------------------|----------------------------------|-------|-------|
| A    | 68,611.078.40                    | 7,202,267.90                    | 2,160,563.00                  | 0.105                            | 0.031                            | 0.160 | 0.654 |
| B    | 50,672.265.60                    | 5,319,188.10                    | 1,595,670.00                  | 0.105                            | 0.031                            | 0.160 | 0.654 |
| C    | 47,322.447.90                    | 4,967,549.78                    | 1,400,180.00                  | 0.105                            | 0.031                            | 0.160 | 0.654 |
| D    | 116,275,169.00                   | 12,205,680.70                   | 3,661,505.00                  | 0.105                            | 0.031                            | 0.160 | 0.654 |

FIGURE 8. Comparison of Tariff rate of Zedan model with that of WERA current model.

practice; with an improved $PF_{opr}$ above 0.9, the consumers can have benefits of SAR 0.1 to 0.9 million per month, that can help in covering the costs of PF improvement equipment and encourage consumers to participate in such practices. It should be noted that the cost and savings indicated in this table are for the feeder under study and not for the industry, as they are supplied by more than one feeder.

IV. SUMMARY

Equation (1) provides the means of optimizing cooperation between consumers and SP to achieve mutual benefits. As indicated above, both sides can achieve a fair and acceptable return, only when consumers are provided the right incentive.

The use of equation (1) does not impede the application of the daytime use process, where during the targeted periods, $T$ can be set to higher values with the same values of $N_i$ and $N_p$, or even others. Consequently, $T_{res}$ will be given in fulfillment of the process.

Field measurements at Saudi Electric Company’s (SEC) substations in Jubail Industrial City for the four industrial plants were completed.

- Data analyses were conducted to evaluate savings in Ohmic losses due to improvement in $PF_{opr}$, which gave recognizable savings in fuel consumption and CO2 emissions.
- The proposed tariff model (Zedan model) was based on the assigned tariff ($T$), assigned $PF_{ref}$, consumer $PF_{opr}$, and a variable factor, $0 \leq N \leq 1$, (equation (1)).

The factor $N$ was selected based on savings in the Ohmic losses in the transmission systems. The study designated two values of $N, N_p$ for a penalty, and $N_i$ for incentive, providing, thereby flexibility to segregate the desired values of incentives and penalties concerning prevailing economic considerations.

- Proposed model and WERA’s current model for industrial tariff are compared (fig. 8). The proposed model includes an incentive to consumers to maintain $PF_{opr}$ above $PF_{ref}$.
- Proposed model can be successfully applied with programmed smart meters to compile $T_{res}$ values for minute intervals, which in effect gives, per interval, accumulated monthly consumption charge.

V. CONCLUSION

The key differences between the two models: PF management protocols and the proposed model are as follows:

- The first is based on average monthly measurements, whereas the latter (proposed in this paper) facilitates measurement over smaller intervals down to a minute.
- The first assigns fixed penalty rates, while the latter’s penalty/incentive rates are segregated and are a function of time, as given by the resulting charging tariff $T_{res}$.
- The takeaways from these differences are:
  1. Lack of focus on critical periods, vs. ability to focus, hence allowing needed catering,
  2. Fixed rates vs. sensitivity towards slight deviation from $PF_{ref}$, as being a function of the degree of deviation.

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TABLE 7. Approximate Energy consumption cost per applied model in SAR.

| Site | Jan-20 | Feb-20 | Mar-20 |
|------|--------|--------|--------|
| A    | 12,531,000 | 8,409,000 | 12,741,000 |
| B    | 7,978,000 | 8,691,000 | 9,501,000 |
| C    | 8,309,000 | 7,700,000 | 8,494,000 |
| D    | 21,932,000 | 29,375,000 | 24,864,000 |
| E    | 12,422,000 | 7,846,000 | 9,363,000 |
| F    | 8,117,000 | 7,527,000 | 8,309,000 |
| G    | 21,415,000 | 28,428,000 | 24,099,000 |
| H    | 109,349 | 173,074 | 12,635,000 |
| I    | 9,501,000 | 947,105 | 127,736 |

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