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Interactive Power Factor Management With Incentives Toward Reduction in Fuel Consumption and Carbon Emission

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ABSTRACT Reducing costs, emissions, and improving efficiency in the electric power networks are becoming urgent. It is, therefore, necessary to apply improvements in the industry's operation, for example maintaining acceptable consumer's operational PF (PF_{opr}) gauged against reference PF (PF_{ref}), where penalties are levied on monthly averaged PF_{opr} below PF_{ref}. The efforts can be enhanced if based on interactive involvement and participation between consumers and services providers (SP's), mainly by 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' PF_{opr}. In this spirit, a novel mathematical model and framework are presented which consist of a time-referenced function relating applicable tariff to PF_{opr}, thus benefiting SPs by reducing capital and maintenance costs, providing flexibility to focus on peak load periods, and rewarding incentives to the consumers maintaining PF in an acceptable range. The model was implemented on measurements at four industrial facilities in the Eastern Province of Saudi Arabia for one year and the results were verified in terms of reduction in network's heat losses, CO_2 emissions, fuel consumption, and the resulting monetary benefits.

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, all as power losses increase. These equate to higher capital investments, operational costs 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 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].

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Most of the international utilities consider specified fees for lower PF_{opr} with respect to PF_{ref}. An extensive review of the literature [4]–[9] indicates, that most of the utilities impose penalties for low PF_{opr} viz a viz assigned PF_{ref}, with varying qualifications for connected kVA, kWh consumption, and range of deviation below PF_{ref}. Consumers with averaged PF_{opr} below reference PF_{ref} are charged a fixed amount per unit of reactive energy. In some cases, energy tariffs have a multiplier or an adjustment for low PF_{opr}. In other cases, a minimum PF_{ref} level is set for penalty and threshold for energy consumption (kWh). In this study, an investigation for alternative billing methodology based on the stated reference [1], using dynamic measurement of PF_{opr} 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 PF_{opr} 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 available electricity efficiently, higher cost is imposed by PF multiplier adjustment [5]. For Oncor Electric Delivery Company (ONCOR), the tariff policy states that if PF_{opr} 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 PF_{opr} 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 PF_{opr} 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, 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 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, Saudi Electricity Company (SEC), based on Water and Energy Regulatory Authority's (WERA) decision [10], charges for non-household consumption PF_{opr} 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 PF_{ref} 0.9 [10]. Thus, the treatment of PF currently adapted is based on the average monthly measurement of the consumer's PF_{opr} with a progressive penalty applied for PF_{opr} lower than the PF_{ref}. This local and international treatment for low PF_{opr} should be adjusted to correct two major shortcomings:

- The monthly average measurement gives misleading information, as it does not allow for 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, still this cannot provide progressive incentives to the consumers, which in turn does not encourage them for promoting further improvements in PF_{opr}, even at a relatively higher marginal investment cost, all subject to it's 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 CO_2 emissions associated with the changes in PF_{opr} 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 CO_2 emissions, and lastly, the relationship of change in PF with the network's current-related heat 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. Lastly, Section 4 summarizes the study outcomes and Section 5 highlights the conclusion.

II. BACKGROUND

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

$$\frac{T_{res}}{T} = N + (1 - N) \times \left(\frac{PF_{ref}}{PF_{opr}}\right) \tag{1}$$

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 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 (kVAh) as:

$$T_{res} \cdot W = T \cdot N \cdot W + T \cdot (1 - N) \cdot \left(\frac{W}{PF_{opr}}\right) \cdot PF_{ref}, \quad (2)$$

which can be interpreted as, consumption charge equals charge on real energy and drawn apparent energy times PF_{ref}.

With available digital meters, the model in (1) allows time-related gradual penalty or incentive for PF_{opr} lower or higher than PF_{ref}, respectively. Since T_{res} is inversely related to PF_{opr}, penalty or incentive increases/decreases with variation in PF_{opr}, an advantage is provided by allowing a gradual increase/decrease in T_{res} per (kVARh), rather than what is currently applied, i.e., a constant penalty or reward irrespective of the degree of deviation in PF_{opr}. 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 award fair and acceptable incentives that encourage consumers to exert efforts and carry the additional investments to maintain a high PF_{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 kWh and consequently lower emphasis on kVAh. The paper presents a reliable basis for a narrow range of N values for each category of consumers with respect to changes made in PF_{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 CO_2 emissions. To establish a reliable base for the approach, and since the instantaneous variation in PF_{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 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 real 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 current related technical losses.

TABLE 1. Energy generation by source in GWh for Saudi Arabia [15].

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

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 CO_2 emissions, the following calculations are adopted based on the 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 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.

C. CO_2 EMISSION

Around 40% of the total CO_2 emissions in Saudi Arabia are attributed to the energy sector, followed by industrial processes and agricultural sectors [15]. Currently, the country is making significant efforts and investments, as well as policy

TABLE 2. Sector-wise CO_2 emissions in million-tons [Mt] for Saudi Arabia [15].

Year/Sector	Electricity & heat producers	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

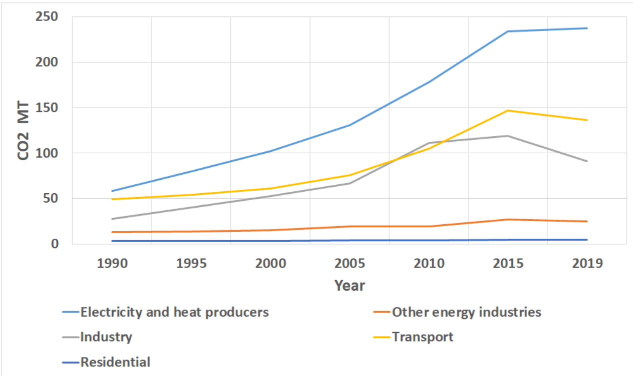

FIGURE 1. Sector wise CO_2 emissions of KSA from 1990 to 2018 [15].

measures to reduce mainly these emissions inline 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 CO_2 emissions. International experience [17] showed that the proposed policies about energy savings and emission reduction could result in a cumulative reduction of 818.3 $MtCO_2$ from 2015 to 2030, compared with the existing policies.

For Saudi Arabia, as shown in table 2, two major sectors contribute heavily to CO_2 production; namely Electricity & Heat Producers, and Transport. These two sectors showed a reduction in CO_2 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 as these two sources result in significantly less total CO_2 emissions. As shown in table 1, there was an 8% decrease in oil consumption, with a similar increase (7%) in Natural Gas usage for energy generation from 2017 to 2018, with almost the same electricity generation.

D. RELATION OF CO_2 EMISSIONS TO CRUDE OIL BARREL

The calculation of CO_2 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]

$$5.8\frac{mBTU}{barrel} \times 20.31\frac{kgC}{mBTU} \times \frac{44}{12}\frac{kgCO_2}{kgC} \times \frac{1}{1000}\frac{mTon}{kg} = 0.43\frac{mTonsCO_2}{barrel}$$

Hence 0.43 metric Tons of CO_2 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 PF_{opr} with the resulting percentage variation in heat losses. Assuming a load X utilizes apparent demand (S), and drawn real demand (P) given as,

$$S = \sqrt{3}VI = \frac{P}{PF}. \tag{3}$$

Assuming that within a period of PF_{opr} changes, both P, and receiving end voltage V are constant, with current (I), operational PF_{opr} for two cases, PF_1 and PF_2. Equation (3) gives,

$$\frac{1}{PF_1} = C_1 I_1, \quad \frac{1}{PF_2} = C_1 I_2, \tag{4}$$

where, C_1 is a constant equal to $\frac{\sqrt{3}V}{P}$. Equation (4) gives,

$$\frac{PF_2^2}{PF_1^2} = \frac{I_1^2}{I_2^2}. \tag{5}$$

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

$$E_{loss_i} = \sqrt{3}I_i^2 Rh = C_2 I_i^2, \quad i = 1, 2, \; C_2 = \sqrt{3}Rh, \tag{6}$$

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

$$\frac{E_{loss_1}}{E_{loss_2}} = \frac{I_1^2}{I_2^2} \tag{7}$$

Equations (5) and (7), provide variation in PF_{opr} as inversely related to the network's thermal losses, similarly to (BTU) and CO_2 emission, and is presented as,

Equation (7), presented with the term $(\frac{E_{loss_1} - E_{loss_2}}{E_{loss_1}})$ gives;

$$Energy\ Loss\ Reduction\ \% = \left(1 - \left(\frac{PF_1^2}{PF_2^2}\right)\right) \times 100, \tag{8}$$

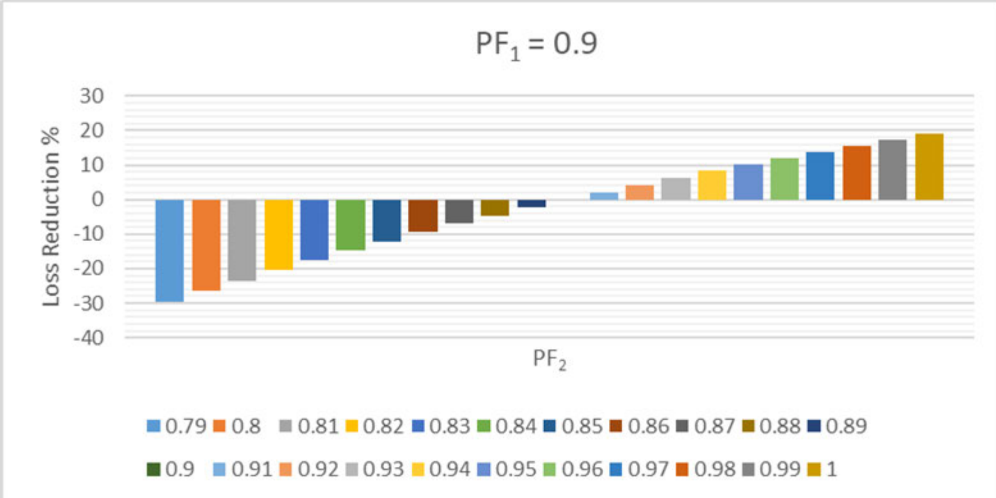

FIGURE 2. Energy loss reduction and PF improvement relation.

Figure 2 shows the relation between loss difference and PF_{opr} improvement.

Although equation (8) is a quadratic relation, however, within the range of PF_{opr} increasing or decreasing for PF_{opr} by a multiple of ± 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 CO_2 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 CO_2 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 CO_2 for 1 GWh load; these results are also shown graphically in figure 3.

Similarly, if a consumer improves PF_{opr} further above PF_{ref} 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.

TABLE 3. Economy of PF improvement for targeted PF of 0.9.

Current operating avg. (PF_1)	Target (PF_2)	Losses Red. [%]	Losses Red. [kWh]	MBTU Red.	Eq. Crude oil barrels	CO_2 em. (mTon)
0.7	0.9	39.51	12440.49	127.58	22.00	11.00
0.72	0.9	36.00	11336.40	116.26	20.04	10.02
0.74	0.9	32.40	10201.20	104.62	18.04	9.02
0.76	0.9	28.69	9034.91	92.66	15.98	7.99
0.78	0.9	24.89	7837.51	80.38	13.86	6.93
0.8	0.9	20.99	6609.01	67.78	11.69	5.84
0.82	0.9	16.99	5349.41	54.86	9.46	4.73

TABLE 4. Economy of PF improvement for targeted PF of 0.99.

Current operating avg. (PF_1)	Target (PF_2)	Losses Red. [%]	Losses Red. [kWh]	MBTU Red.	Eq. Crude oil barrels	CO_2 em. (mTon)
0.9	0.99	17.36	5465.21	56.05	9.66	4.83
0.92	0.99	13.64	4295.70	44.05	7.60	3.80
0.94	0.99	9.85	3100.48	31.80	5.48	2.74
0.96	0.99	5.97	1879.57	19.28	3.32	1.66
0.98	0.99	2.01	632.95	6.49	1.12	0.56

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 between business partner, i.e., consumer, and SP.

To arrive at the required N, the term (T/T) is subtracted on both sides of equation (1), giving,

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

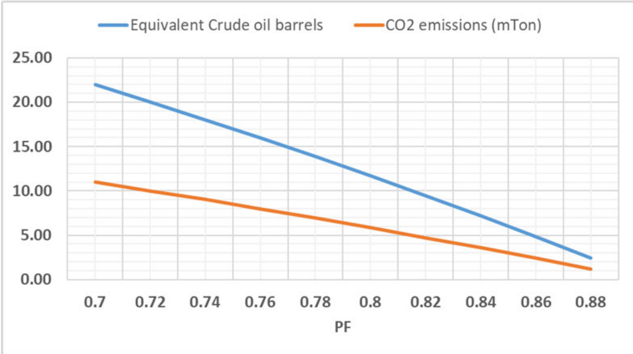

FIGURE 3. Relationship of PF_{opr} improvements up to 0.9 for 1 GWh load with equivalent crude oil barrels and CO_2 emissions in metric tons.

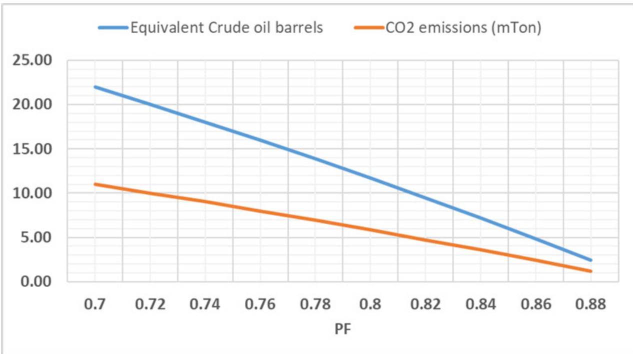

FIGURE 4. Relationship of PF_{opr} improvement up to 0.98 for 1 GWh load with equivalent crude oil barrels.

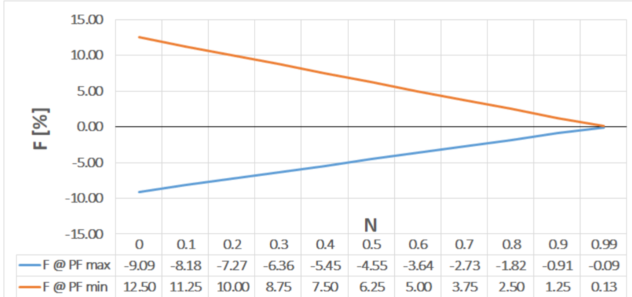

FIGURE 5. Relation of N with F% for PF_{ref} = 0.9, PF_{max} = 0.99, PF_{min} = 0.8, and T = 0.18.

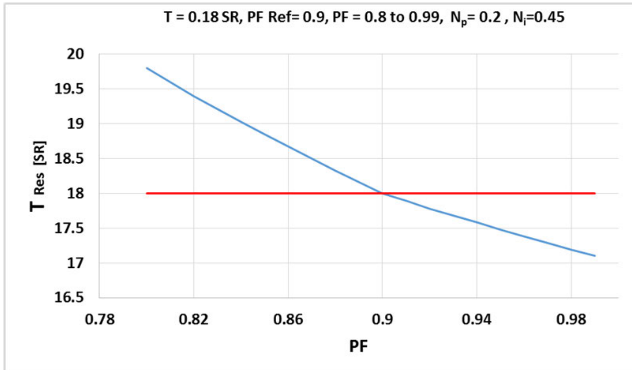

FIGURE 6. Effect of two different values of N on T_{res}.

Equation (9) gives,

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

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 $P_{max} = 0.99$ 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. 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_i 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 "reprogram" the existing 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 side, there is no discontinuity observed.

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.

TABLE 5. Choice of *N* for studied sites in the industrial sector.

Site	Avg. Active Energy (GWh/ Mo.)	Shared total losses (GWh/ Mo.)	Shared Ohmic losses (GWh/ Mo.)	Total losses: Energy consumption (F_p)	Ohmic losses: Energy consumption (F_i)	N_p	N_i
A	68.6	7	2	0.105	0.03	0.16	0.65
B	50.7	5.3	1.6	0.105	0.03	0.16	0.65
C	47.3	5	1.5	0.105	0.03	0.16	0.65
D	116	12	3.7	0.105	0.03	0.16	0.65

1) Find the average kWh consumed in a period of one month: X 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 5. 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. (2/27/33) dated 21/10/1433 H [10]), 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 charged at 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)).

$$T_{res}\ (Zedan\ model) = \begin{cases} 0.18\left[0.16 + (1-0.16)\,\dfrac{0.9}{PF}\right] \times SAR/kWh : PF < 0.9 \\ 0.18\left[0.654 + (1-0.654)\,\dfrac{0.9}{PF}\right] \times SAR/kWh : PF \geq 0.9 \end{cases} \tag{11}$$

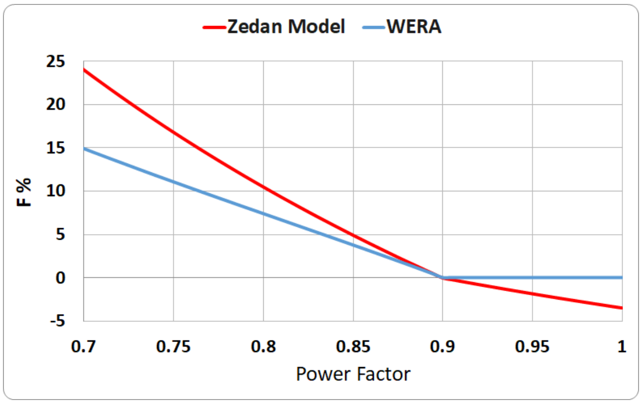

FIGURE 7. Comparison of F% of Zedan model with that of WERA model.

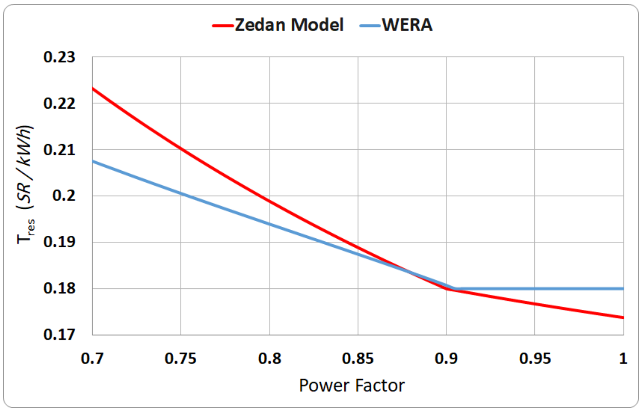

FIGURE 8. Comparison of tariff rate of Zedan model with that of WERA current model.

$$T_{res}\ (WERA\ model) = \begin{cases} 0.18 + 0.05(tan\left(cos^{-1}PF\right) - tan\left(cos^{-1}0.9\right)) \\ SAR/kWh\ PF\ < 0.9 \\ 0.18\ SAR/kWh\ PF \geq 0.9 \end{cases} \tag{12}$$

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, 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 industrial consumers of the proposed study, it is noted that all four of them operated on PF_{opr} above 0.9. Table 6 compares the resulting tariff due to Zedan model and WERA's current practice; with an improved PF_{opr} above 0.9, the studied consumers can have benefits of SAR 0.1 to 0.9 million per month for the initial months of the year 2020. Such incentives can help in covering the costs of PF improvement equipment and encourage consumers to participate in such practices.

TABLE 6. Approximate energy consumption cost per applied model in SAR.

Approximate Monthly Consumption Cost (million SR)	Site	Jan-20	Feb-20	Mar-20
Consumption cost as per WERA current model	A	12.5	8.4	12.7
	B	8	8.7	9.5
	C	8.3	7.7	8.5
	D	22	29.3	24.8
Consumption cost as per Zedan model	A	12.4	8.3	12.6
	B	7.8	8.6	9.4
	C	8	7.5	8.3
	D	21.4	28.4	24
Saving	A	0.11	0.1	0.1
	B	0.13	0.13	0.14
	C	0.2	0.17	0.19
	D	0.5	0.9	0.8

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 nor to feed-in tariff process, where during the targeted periods, T can be set to different value with the same values of N_i and N_p or even others. Consequently, T_{res} will be given in fulfillment of the process.

Specific points can be summarized as follows:

- Field measurements at four industrial plants in the Eastern Province of Saudi Arabia 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 CO_2 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.
- Zedan model and WERA's current model for industrial tariff are compared (fig. 8). Zedan model includes an incentive to consumers to maintain PF_{opr} above PF_{ref}.
- Zedan model can be successfully applied with programmed digital 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, as proposed, 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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