CORPORATE WIDE POWER FACTOR CORRECTION APPLICATION: ECONOMIC AND TECHNICAL ASSESSMENT

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Abstract –The Electricity and Cogeneration Regulatory Authority (ECRA) in Saudi Arabia issued a directive to charge commercial and industrial customers for reactive power consumption. Consequently, Saudi Aramco formed a taskforce to assess the economic and technical impact on the company as a result of the new ECRA resolution. Relevant data were collected from more than eight hundred (800) sites and potential increase in utility charges was estimated to be twenty million dollars ($20MM) on annual basis. Corrective measures were studied from both technical and economic standpoints and recommendations were made for each applicable facility. The recommendations included utilizing onsite synchronous machines and/or installation of Power Factor Correction (PFC) capacitor banks to locally support the reactive power requirements. PFC capacitor banks, being the most common solution, were studied in detail, and directions were provided to avoid potential compromises in system reliability.

Index Terms — Power Factor Correction, Net Present Value, Harmonic Resonance, Reactive Power Charges

I. INTRODUCTION

A. Technical Overview

Useful working power (mechanical energy, heat, light, etc.) is produced by the effect of active power (P) conversion. The reactive power (Q) doesn't produce any useful power. Yet, the reactive power enables the active power to be transmitted to electrical loads. The power factor is the ratio of real power to apparent power and expressed as:

$$PF = \frac{P}{S} = MW/MVA$$

Power factor reflects how efficiently the electric power is being utilized. The closer the power factor to unity (1), the less reactive power is produced and the more active power can be generated and transmitted.

Reactive power (Q) takes up space on transmission lines leaving less room for active power (P). Furthermore, reactive power is difficult to transfer over long distances and is attributed to recent major blackouts worldwide.

Utilities in Saudi Arabia gradually started imposing penalties on industrial and commercial customers with power factor below 0.95. For large industrial customers the penalties could add up to tens of millions of dollars in additional utility charges on annual basis.

B. Background

The Electricity and Co-Generation Regulatory Authority (ECRA) ruled that a tariff consumption of $13.33/Mvarh will be applied when reactive power consumption exceeds 0.9 starting 15 July 2017 at the point of interface (POI) with the public grid operated by Saudi electricity Company (SEC). Starting 22 May 2022 the far more stringent of 0.95 will be applicable [1].

A task force surveyed all Saudi Aramco plants and gathered active and reactive power data to assess the current situation. Power factor correction requirements were studied and budgetary cost proposals were obtained from various manufacturers to estimate the total cost of implementation.

Initially, more than seven hundred (700) SEC meters were surveyed to determine ECRA resolution applicability as shown in Figure *1*.

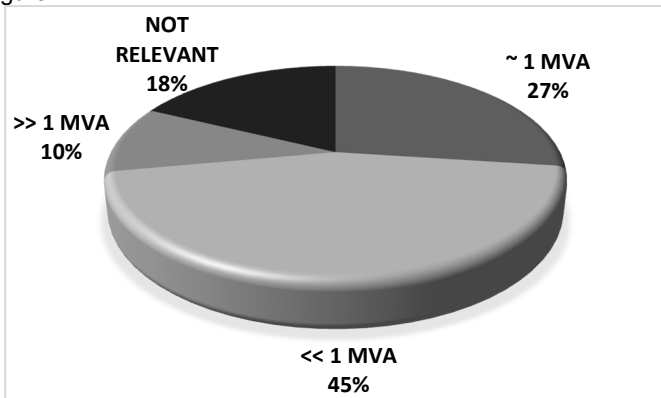

Figure 1 SEC meter survey

In addition, one hundred and fourteen (114) major facilities were further categorized as follows (see Figure *2* for illustration):

- Facilities with synchronous motor where power factor could be corrected by modification of motor's excitation control,
- Facilities with cogeneration which are excluded from ECRA's ruling,
- Facilities that have been mothballed, and
- Facilities where implementation of power factor correction would yield economic benefit.

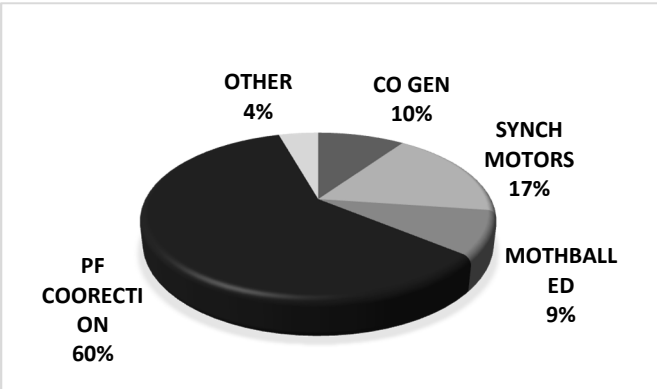

Figure 2 Major Facilities

The following types of facilities were excluded from the analysis since they are not included in ECRA's ruling:

- Facilities that are not directly connected to the grid, and
- Facilities with less than 1 MVA connected load.

C. Objectives

The objectives of the Power Factor Correction Technical and Economic Assessment were:

- Maximizing profitability by reducing electric utility bills,
- Complying with applicable Grid Code requirements stipulating that sites and facilities supplied at 115 kV or above shall ensure that the power factor at POI does not fall below 90% lagging at any time,
- Optimizing fuel consumption and improve energy savings, and
- Efficiently meeting the country's energy demand and contribute to the development of the economy by increasing system capacity, deferring capital investment and reducing energy losses.

D. Approach

The task force surveyed all Saudi Aramco plants and facilities and gathered active and reactive power data to assess the current situation as follows:

- Reaching out to Saudi Aramco's power control center (PCC) to provide active and reactive power hourly readings for a representative year,
- Trending power factor variations based on data provided by the PCC. See attachment-A for a sample trend.
- Obtaining missing information – where applicable - from power system analysis software.
- Estimating the net present value (NPV) of utility reactive power charges for all company facilities as stipulated in ECRA's ruling.
- conducting market research to specify proper corrective solutions to avoid the utility reactive power charges,
- obtaining budgetary proposals to estimate the total cost of solution implementation,
- Calculating the total NPV in terms of cost avoidance and tabulate the results, and
- Providing recommendations to concerned plants to conduct site specific studies and implement remedial actions.

II. CORRECTION ALTERNATIVES TECHNICAL EVALUATION

The task force evaluated various correction alternatives to correct power factor and categorized them as follows:

A. Operational Approach

Many Saudi Aramco plants have synchronous motors which could be utilized to correct power factor. Overexciting the motor would generate reactive power with leading power factor.

In one facility, originally the power factor was 0.8 at the POI. However, there are twelve (12) - 16000 HP synchronous motors available within the facility. By adjusting the excitation for each motor, the 0.95 target power factor can achieved at the POI. This being said, the motor thermal limits should be carefully examined prior to adjusting the excitation.

Overall, ten (10) facilities were identified where motor excitation adjustment would support the plant reactive power demand without the having the power factor falling below 0.95 at the POI.

B. Equipment Approach

Power factor could be corrected by installing additional equipment such as capacitor banks and synchronous condensers.

1) *Capacitor Banks:* There are three options for installing power factor correction capacitor banks as follows:
   - Low voltage Metal Enclosed- indoor/outdoor
   - Medium Voltage Metal Enclosed- indoor/outdoor
   - Medium Voltage Rack-Mount- outdoor

   Installing medium voltage banks would be more preferred since it takes more advantage of the load diversity than if installed at low voltage level. However, in some cases the site specific analysis might reveal that installing the capacitor banks at low voltage is more feasible.

   Installing outdoor metal enclosed capacitor banks has some concerns related to temperature ratings. Some manufacturers propose integral HVAC installations to meet the temperature criteria stipulated in company standards (50 degrees Celsius), which might cause maintenance concerns. Therefore, the installation of metal enclosed capacitor banks was recommended to be limited to indoor substations. If no room is available inside an existing substation, rack-mount out door capacitor banks, which are widely used by SEC, was recommended to be considered.
2) *Synchronous condensers:* Synchronous motors are installed to drive large mechanical loads such as oil shipper pumps and gas compressors. In addition, they could provide reactive power to the system when the motor excitation control is set properly. Synchronous condensers are similar to synchronous motors without a mechanical load. In other words, synchronous condensers are designed specifically for reactive power compensation. Synchronous machines are active elements and can respond to power factor correction in a dynamic manner. However, they require more periodic maintenance than capacitor banks. Generally, the average installed cost for synchronous condensers varies from $50 to $200 per kvar and maintenance runs about from $0.8 to $1.6/kvar per year.

Overall, the taskforce considered capacitor banks for the economic and technical analysis conducted in this report since it is the prevalent solution in the industry. However, this does not rule out the application of other solutions provided they prove their feasibility.

C. Ancillary Services and Power Wheeling

Many utilities around the world pay for reactive power support provided by customers, which is often referred to as ancillary services. To date, no such agreement has been achieved with ECRA. Nonetheless, having such agreement in place does not remove the economic benefit related to power factor improvement at Saudi Aramco sites, as more ancillary services (reactive power) can be sold.

Power wheeling is the transmission of the reactive and/or active power from the buyer (SA facility) to seller (SEC source) then to another same buyer's facility. The active/reactive power provided by the buyer may be due to availability of cogeneration facility within the site or ring system configuration such that the buyer (SA) is connected to into a back to back to the seller through same/another facility within the same vicinity.

Overall, nine (9) cases were identified where considering power wheeling would result in eliminating reactive power charges.

III. ECONOMIC ANALYSIS

A. Data Source

Power system parameters for the power factor correction study were extracted from the PCC supervisory control and data acquisition (SCADA) system for most of company's facilities with 100 percent confidence level. The remaining facilities did not have Remote Terminal Units (RTU) to extract data from. For those facilities power system analysis software was utilized to obtain the real and reactive power parameters of (assumptions were made based on typical consumption for similar facilities.

Facilities that have co-generation and/or synchronous motors, or that are not directly connected to the public grid and/or consume less than 1 MVA and/or are of residential nature were excluded from the analysis.

B. Reactive Power Charges Forecast

Graphical representations (charts) were created for all facilities based on formulas detailed in Attachment-A. In addition, attachment-A includes a sample chart that reflects the active and reactive energy consumption for a representative year as well as the forecasted utility reactive power charges based on ECRA's ruling. This kind of chart was developed for all subject facilities.

ECRA's ruling would translate into well over $ 100 million in net present value (NPV) of utility reactive power charges for all of the company's facilities studied.

C. Net Present Value Calculation Methodology

The methodology used for Power Factor Correction Technical and Economic Assessment is the discounted cash flow (DCF) valuation.

The value of the power factor correction project is the net present discounted value of future expected cash flows. The approach accounts for the time value of money; that is to say it takes into consideration the fact that a dollar received today is worth more than a dollar received tomorrow. Discounted cash flow analysis accounts for the underlying risk of a project through the choice of the discount rate. The discount rate is the risk-adjusted opportunity cost of capital.

The assessment employed DCF analysis based on decremental cash flows. The methodology compares the existing base line – i.e. paying penalty charges - or to a number of investment timing options – some of which to incur penalty charges for a limited duration.

The cash flows for potential power factor correction implementation projects were expected future cash flows. They were entered as the most realistic expectation of future cash flows, not as the most optimistic or most pessimistic outcome.

Cash flows included the effect for inflation, defined as a change over time of the economy-wide price level. Inflation is equivalent to a loss of buying power of a unit of currency in the future.

Before discussing the necessary adjustments made to cash flows it is useful to provide some definitions.

Escalation measures the actual increase in the cost or price of a specific item. It is frequently expressed as a percentage change per year and reflects changes in relative prices, that is, changes in prices relative to other items, and nominal changes, that is changes in general background inflation.

Inflation is a broad measure of the change in the general price level over time. It is constructed as an index and measured in percentage change per year. The index is designed to reflect a basket of goods and services that represents what the representative consumer buys (for the consumer price index) or what the entire economy produces (for the GDP deflator). The GDP deflator measures the loss of purchasing power of the currency.

Nominal rates, such as nominal discount rates, rates of return or interest rates include inflation and measure the actual return or interest received on an investment.

Real rates in contrast adjust for inflation and measure the return over and above inflation. In other words real rates measure the gain to investors after they have paid for the loss of purchasing power.

Current or nominal dollars (or units of currencies) are the actual amounts received or spent at any time and include the effects of cost escalation. They are the equivalent to nominal rates and must be used with them when conducting economic evaluation.

Constant or real dollars (or units of currencies) are current dollars adjusted for inflation or corrected for the loss of buying power. Constant dollars are expressed with reference for a base year, say 2015. Constant (year) 2015 dollars today reflect the same purchasing power as the dollar in the year 2015. Constant dollars must be discounted using the appropriate inflation rate to obtain a suitable real rate.

Economic evaluations carried out as part of the Power Factor Correction Technical and Economic Assessment used nominal cash flows, i.e. current currency units including inflation, and nominal discount rates.

The Net Present Value (NPV) is the present value of all future cash flows. In its most general formulation all cash flow patterns can be considered, including those that have cash outflows not only at time zero, but also in the future. The NPV shows the amount of value added as a currency amount, while incorporating the time value of money. The reinvestment assumptions are the most realistic, assuming that cash flows can be reinvested at the opportunity cost of funds. This is almost always achievable simply by starting to pay down the sources of capital. A project's net present value is given as:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t}$$

CFt = net post-tax cash flow at time t for an all equity firm, and r= required rate of return.

The most theoretically sound decision criterion when evaluating projects is the NPV. Economic value is created when investments earn at least their risk-adjusted opportunity cost of capital. In terms of discounted cash flow analysis, this means that a project or investment must have a positive net present value at the appropriate discount rate to be considered economic. The decision rule is as follows:

If NPV>0 → invest

If NPV<0 → do not invest.

A positive NPV is a necessary condition for any project to proceed. In other words a negative NPV rules out a project because that means effectively that a project is not earning its opportunity cost of capital, thereby destroying economic value.

D. Assumptions

The following assumptions were adapted for the economic evaluations and are – among other - based on budgetary proposals obtained from various manufacturers:

- Cost power compensation device: $35,000/Mvar
- Ratio installed cost / equipment cost: 2.5
- Capex power factor improvement per 1 Mvar (suitable for indoor installation): $87,500/Mvar
- Outdoor installation cost multiplier: 130%
- Fixed cost building: $675,000/ power compensation device
- Fixed cost main power cable: $3,200/power compensation device
- Ratio opex/ capex: 2.0%
- Cost escalation factor: 3.0%
- Tariff escalation factor: 0.0%
- Discount rate: 5.0%
- End of economic life: 2040

E. Assessment Results

A summary table was produced showing for each of the 114 facilities studied the following information:

- annual reactive energy charges at each site if no power factor correction is implemented in period 2017 to 2021,
- annual reactive energy charges at each site if no power factor correction is implemented starting from 2022,
- reactive power compensation required to achieve 0.95 lagging power factor,
- capital expenditures (Capex) at each site to procure and install power factor correction equipment to achieve 0.95 power factor,
- power factor correction project completion year that yields maximum NPV (whilst incurring reactive energy charges until project completion), and
- overall NPV improvement as a result of implementing power factor correction at respective each site.

F. Findings

Analyzing the assessment results yielded several findings.

- Implementing power factor correction measures was economically attractive at 68 out of the 114 facilities studied in detail
- The estimated utility reactive power charges for the 68 identified facilities based on ECRA ruling are $6.0 million per annum (0.90 lagging power factor) in the period 15 July 2017- 21 May 2022, and thereafter $19.5 million (0.95 lagging power factor).
- The total capital expenditure to install power factor correction for the identified facilities is $24.49 million in case the correction equipment is installed outdoor, whereas the capital expenditure would equal $64.15 million in case the equipment would be installed in new dedicated buildings.
    - The total Net Present Value in terms of cost avoidance is: $121 million when the equipment is installed outdoor, or $52 million when the equipment is installed in new dedicated buildings.

IV. CONSIDERATIONS FOR APPLYING POWER FACTOR CORRECTION CAPACITOR BANKS

Adding capacitor banks to an electrical system could have an adverse impact on the system if it is not properly applied. The presence of harmonic in the system could lead to an undesirable results. Therefore, the capacitor bank has to be properly designed to avoid such results.

A. Capacitor banks and Resonance

Harmonics exist in power systems due to the presence of non-linear loads (i.e. power electronics) and also due to non-linear behavior of some linear loads. Harmonics is an undesirable factor in the power networks causing different harmful outcomes ranging from minor trips to major equipment failures. Thus, one aspect of the power quality (PQ) of power systems is the percentage of harmonics in the networks. The most common indices of harmonic measurement are Current Total Harmonic Distortion (ITHD) and Voltage Total Harmonic Distortion (VTHD), which are the ratio of the harmonic content to the fundamental quantity as follows (same definition applies for ITHD) [2] [3]:

$$VTHD = \sqrt{\frac{\sum squares\ of\ amplitudes\ of\ all\ voltage\ harmonics}{square\ of\ the\ amplitude\ of\ the\ fundanental\ voltage}}\ x\ 100\%$$

With PFC capacitor banks added to the electrical system, these indices are expected to increase greatly by creating parallel resonance points at the bus where the capacitor is connected. The parallel resonance point is created because the new capacitor bank is now in parallel with inductive power system network which can be approximated by a single inductor. The parallel resonance point can be approximated as follows:

$$h_r = \sqrt{\left(\frac{MVAsc}{MVAR}\right)}$$

Where:

h_r Parallel Harmonic Resonance; $h_r = \frac{f_r}{60}$;

f_r The resonance frequency

$MVAsc$ Available short circuit power at the capacitor connection

$MVAR$ Size of capacitor bank in Mvar

Commercially available power system simulation software have the option to run frequency scan at pre-specified buses. The frequency scan demonstrates the variation of system impedance versus frequency. As the frequency approach the parallel resonance point, the system impedance approaches infinity as shown in figure 3 where the system is resonant at the 7th harmonic:

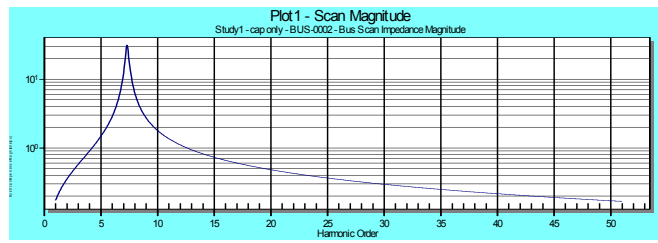

Figure 3: Frequency scan- Parallel resonance at the 7th harmonic

Having a parallel resonance point in the electrical system is not a problem by itself. The problem occurs with the presence of a specific load's harmonic that matches the parallel resonance frequency of the system. This matching will lead to amplifying this harmonic and resulting in excessive VTHD values on the bus where the capacitor is connected. Consequently, all loads connected to this bus will start to draw distorted current leading to premature failures in various equipment in the system [3]. Therefore, the company standards states the current and voltage total harmonic distortion shall not exceed limits identified in IEEE- 519 at the PCC. Furthermore, specifies the PCC as the switchgear bus.

As an example, six pulse variable frequency drives mainly produce the 5th and 7th harmonics. This is based on the following formula to determine the characteristic harmonic based on the number of pulses (diodes) in the front end of a VFD/UPS [2]:

$$h = np \pm 1$$

Where:

h Harmonic order

p Number of pulses (number of diodes in the rectifier bridge in the front end of a VFD or a UPS)

n Integer, 1, 2, 3, 4…

Having such a drive in the system will likely to result in excessive current and voltage total harmonic distortion. This is because it produces the 7th harmonic that matches the parallel resonance point of the system. This will cause excessive current and voltage harmonic distortion leading to premature failures in various system components including the capacitor bank itself. Such events should be avoided in the design phase of PFC applications and the following sections introduces a simplified methodology and case study to illustrate this idea.

B. Methodology for PFC capacitor bank application

Before installing PFC capacitor banks, a special attention should be given to the harmonic distortion constraints as specified in company and international standards (IEEE 519). Figure 4 for recommended design procedure for passive harmonic filter/PFC bank with reactor [2]:

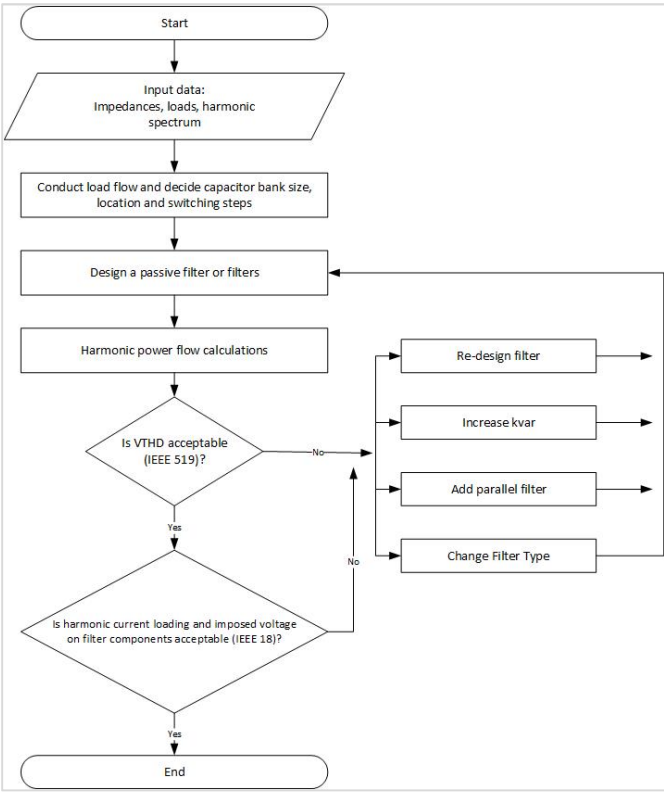

Figure 4: Harmonic Filter Design Methodology for PFC Application [2]

In order to prevent any undesirable events associated with PFC application, frequency scan analysis is conducted at each capacitor's step and for each possible system configuration. This should be followed by a harmonic load flow analysis to determine whether current and voltage total harmonic distortions are within acceptable limits or not. If a harmonic resonance problem is discovered, a detuned filter shall be specified where a reactor is added in series to the capacitor element. The reactance is chosen to form a series resonance circuit at a frequency below the first industrial harmonic which is the 5th. Typically, for power factor application the detuning is chosen at the 4.2nd harmonic order, whereas for harmonic filtering application, the tuning is chosen at the 4.7th harmonic order to partially absorb the fifth harmonic. This is referred to as a single tuned filter. A multi-tuned filter shall be designed to absorb multiple harmonic orders if needed [2] [4] [5].

As illustrated in Figure 4, site measurements including load profile and harmonic spectrum are essential for proper filter design. Figures 5 and 6 demonstrate sample measurements taken at main 13.8 kV switchgear bus at one of Saudi Aramco plants. The waveform signature reflects a 12 pulse VFD behavior, which is actually present at the plant.

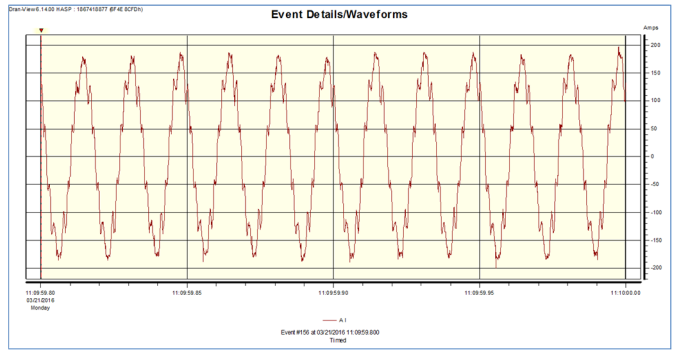

Figure 5: Voltage Waveform

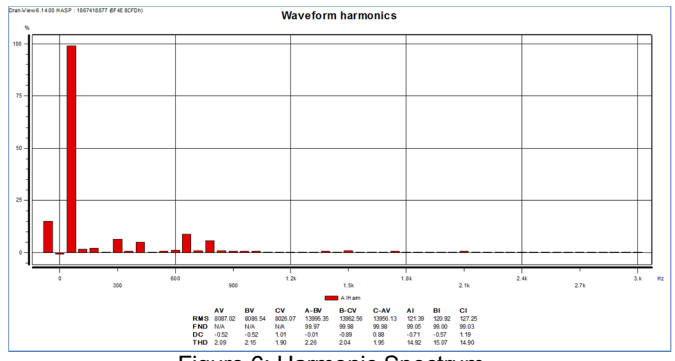

Figure 6: Harmonic Spectrum

C. *Case Study*

System shown in figure 7 represents a typical Saudi Aramco primary distribution scheme at 13.8 kV. The double ended substation has been considered operating with the tie breaker closed and one incomer breaker open (i.e. single ended). In addition, 4 MVA nonlinear (6 pulse drive) load and 40 MVA linear load (motors) were considered. For each of the cases below, the following is illustrated as applicable:

- Load flow single line diagram (SLD)
- Voltage waveform at the 13.8 kV bus
- Voltage harmonic spectrum at the 13.8 kV bus
- Impedance frequency scan at the 13.8 kV bus
- Harmonic load flow single line diagram

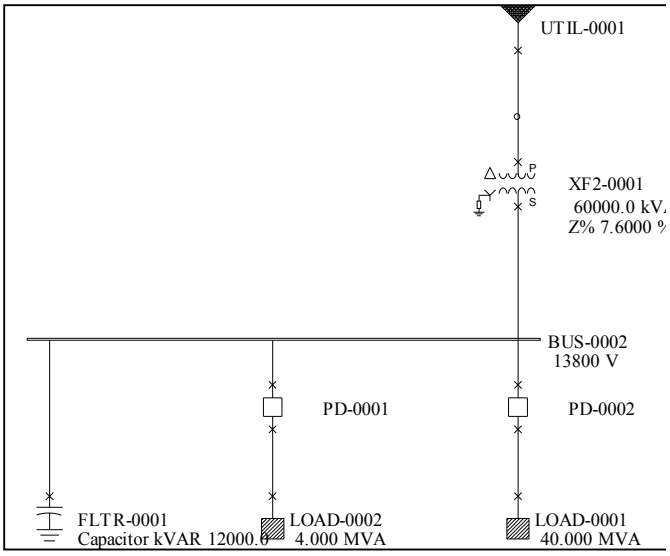

Figure 7: Single Line Diagram of a Typical Saudi Aramco Distribution System

1) *Case 1:* capacitor with motor load: The non-linear load is de-activated and the PFC capacitor banks is installed to correct the power factor to 0.95 for a linear load (40 MVA). The following figures 8-10 show the single line diagram (SLD), the voltage waveform and the frequency scan after the PFC capacitor bank application

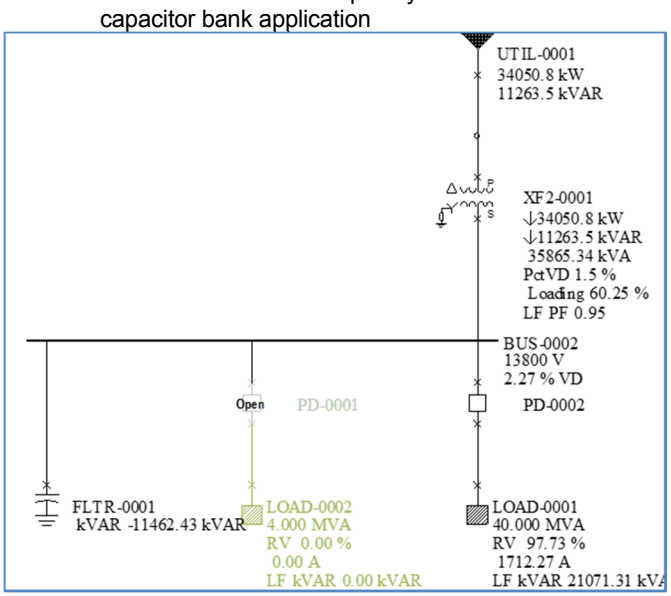

Figure 8: Case 1 Load flow SLD

As expected, the voltage waveform is free of distortion due to absence of non-linear load.

2) *Case 2- capacitor with motor load and 10% nonlinear load:* A 4 MVA nonlinear load is introduced into the system (Load-0002).Figure 12-14 demonstrate an excessive VTHD with a value of 5.5% at the point of common coupling (PCC), which is violating the harmonic distortion limits identified in company standards.

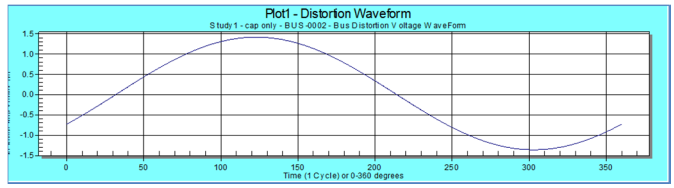

Figure 9: Case 1- Voltage waveform at the 13.8 kV bus

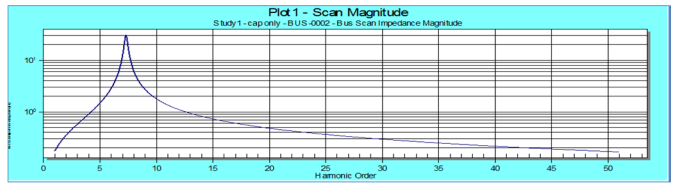

Figure 10: Case 1- Frequency scan at the 13.8 kV bus

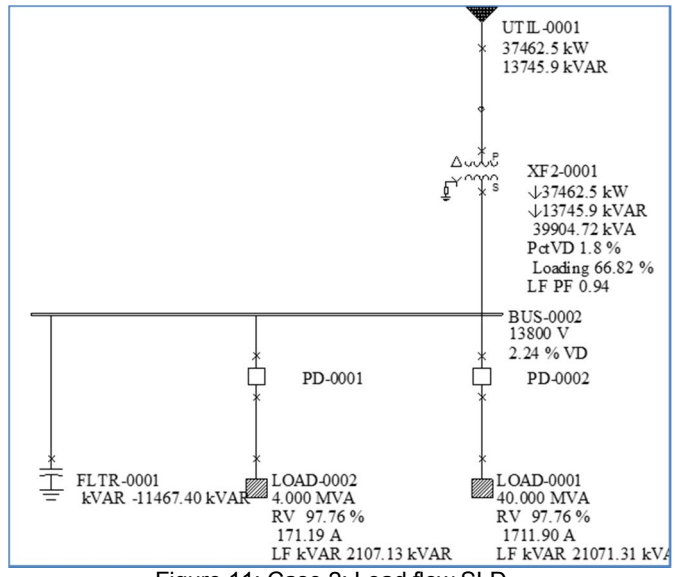

Figure 11: Case 2; Load flow SLD

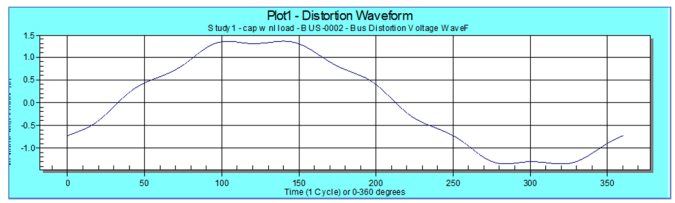

Figure (12): Case 2; Voltage waveform at the 13.8 kV bus

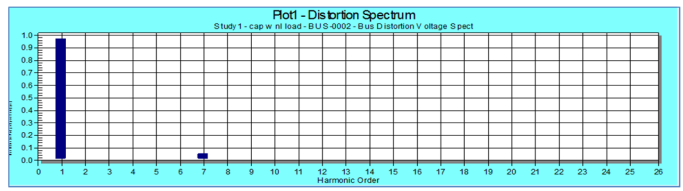

Figure 13: Case 2- Voltage Harmonic Spectrum at the 13.8 kV bus

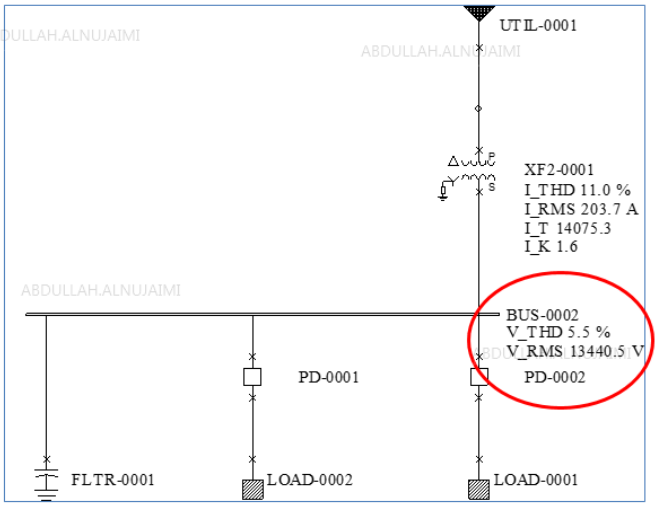

Figure 14: Case 2-Harmonic load flow at the 13.8 kV bus

3) *Case 3- A detuned bank (Filter) with motor load and 10% nonlinear load:* A filter design (capacitor bank with a series reactor) was considered to meet the harmonic distortion limits, the filter was detuned at 4.2th order to force the parallel resonance point to be away from the common harmonic orders generated by the non-linear loads. It is noted that the voltage waveform is now much cleaner than the previous case. Furthermore, the VTHD at the point of common coupling is reduced to 0.6%; which is acceptable by company standards, Figure 15-19.

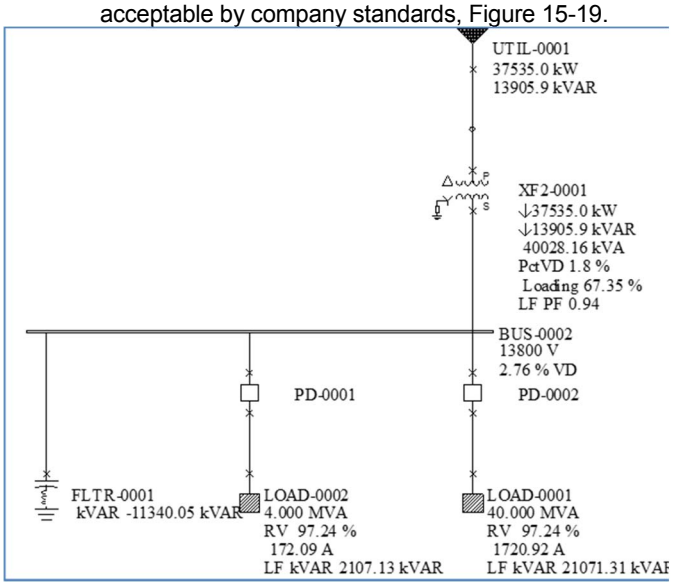

Figure 15: Case 3- Load flow SLD

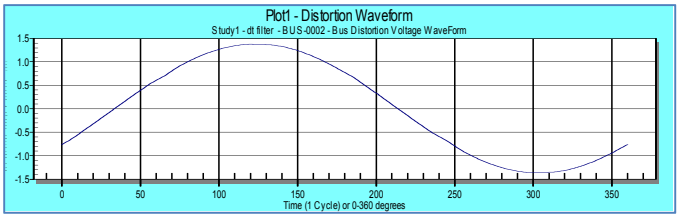

Figure 16: Case 3- Voltage waveform at the 13.8 kV bus

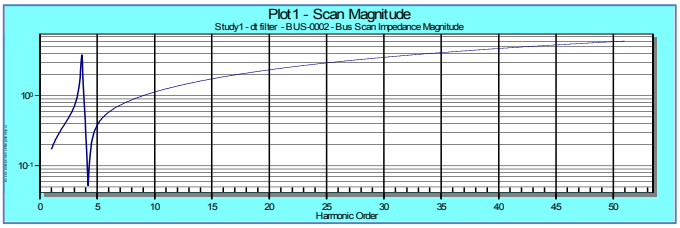

Figure 17: Case 3- Frequency scan at the 13.8 kV bus

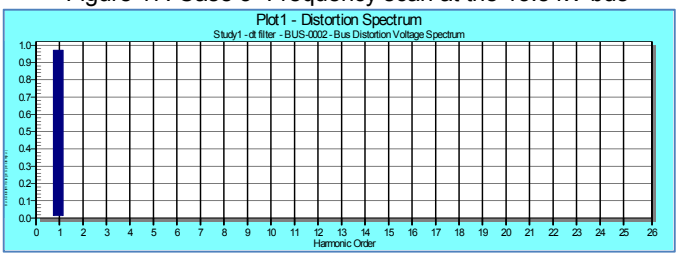

Figure 18: Case 3- Voltage Harmonic Spectrum at the 13.8 kV bus

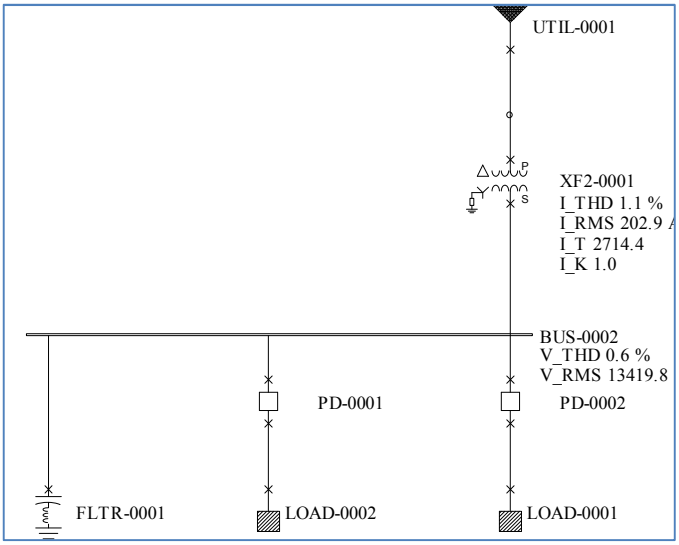

Figure 19: Case 3- Harmonic load flow at the 13.8 kV bus

4) *Case 4- Capacitor with motor load and 10% nonlinear only- 2Mvar step:* As illustrated in the design methodology, the resonance shall be checked for all possible steps of the added capacitor banks to ensure that PFC applications will not cause any harm to the system under any circumstances. In this case study, a two (2) kVAR step was examined and it caused a shift in the parallel resonance point from the 7th harmonic (Case 2) to the 17th harmonic. The 17th harmonic is another common harmonic order caused also by with 18-pulse drives. The total harmonic distortion is now 6.1% violating the specified limits as shown in figure 24. Figures 20- 24 explain this case study graphically.

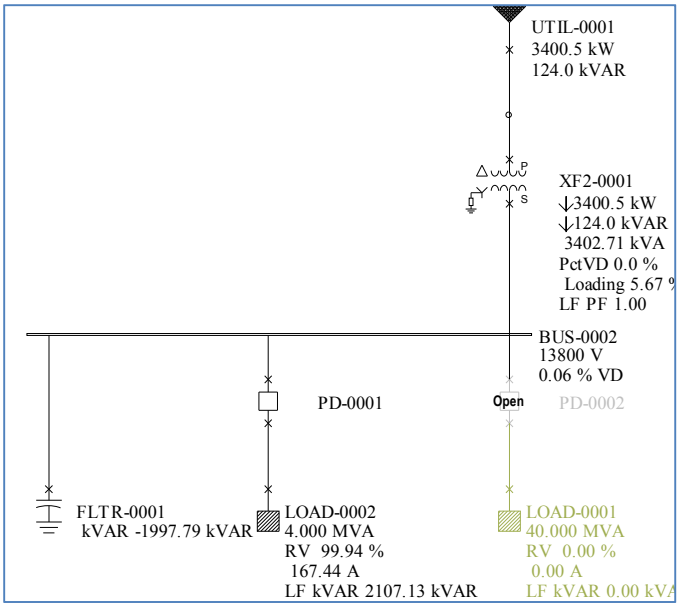

Figure 20: Case 4- Load flow SLD

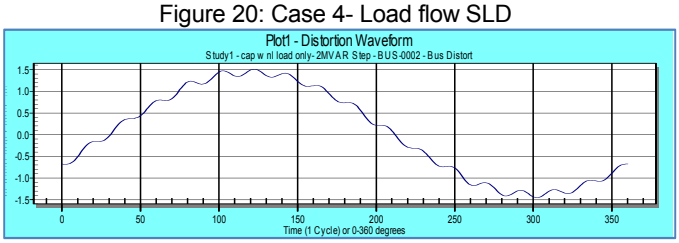

Figure 21: Case 4- Voltage waveform at the 13.8 kV bus

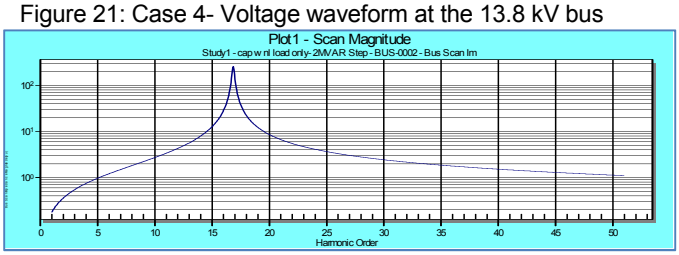

Figure 22: Case 4- Frequency scan at the 13.8 kV bus

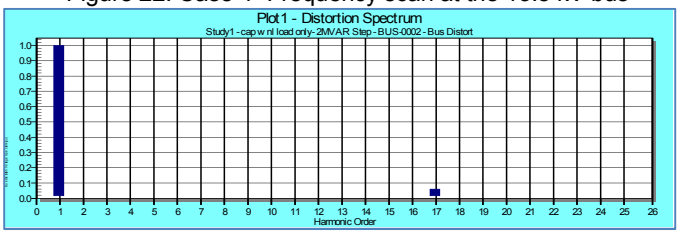

Figure 23: Case 4- Voltage Harmonic Spectrum at the 13.8 kV bus

5) *Case 5- A detuned bank (filter) with motor load and 10% nonlinear only- 2 Mvar step:* Similar to case (3), the de-tuned filter is now applied at 4.2th order and the parallel resonance point is now shifted to a value below 4.2. Hence, the total harmonic distortion is now reduced to 0.9% in compliance with company standards, Figures 25-29.

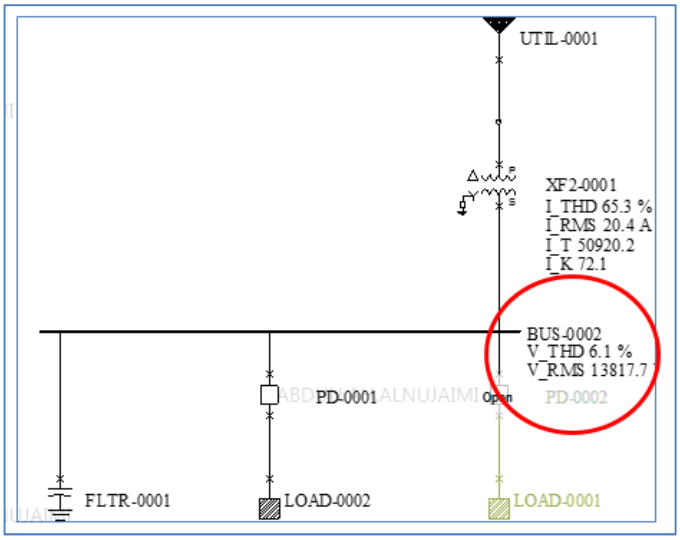

Figure 24: Case 4- Harmonic load flow at the 13.8 kV bus

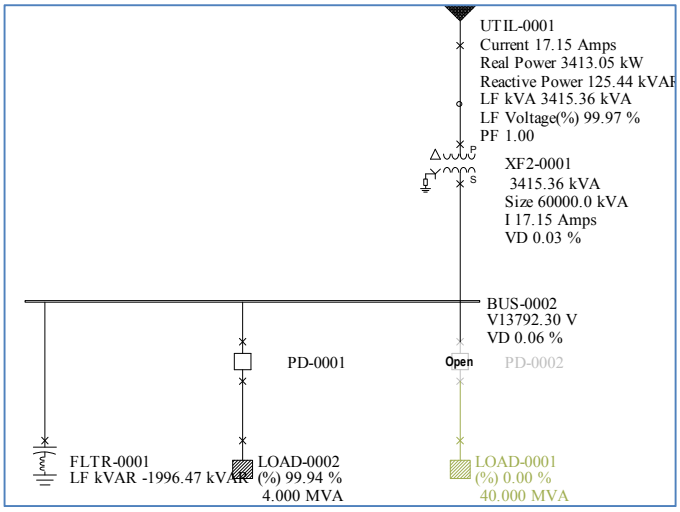

Figure 25: Case 5- Load flow SLD

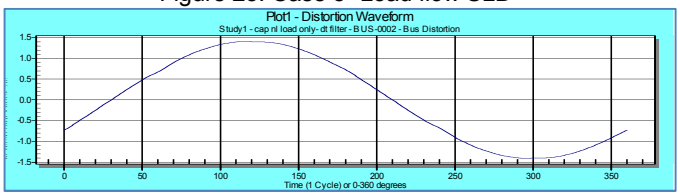

Figure 26: Case 5- Voltage waveform at the 13.8 kV bus

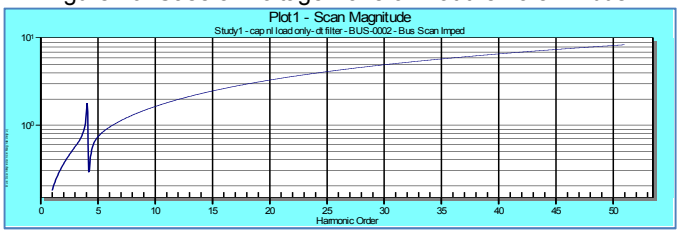

Figure 27: Case 5- Frequency scan at the 13.8 kV bus

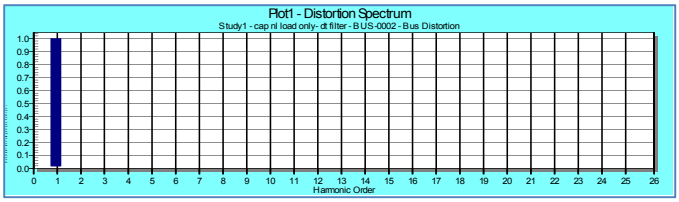

Figure 28: Case 5- Voltage Harmonic Spectrum at the 13.8 kV bus

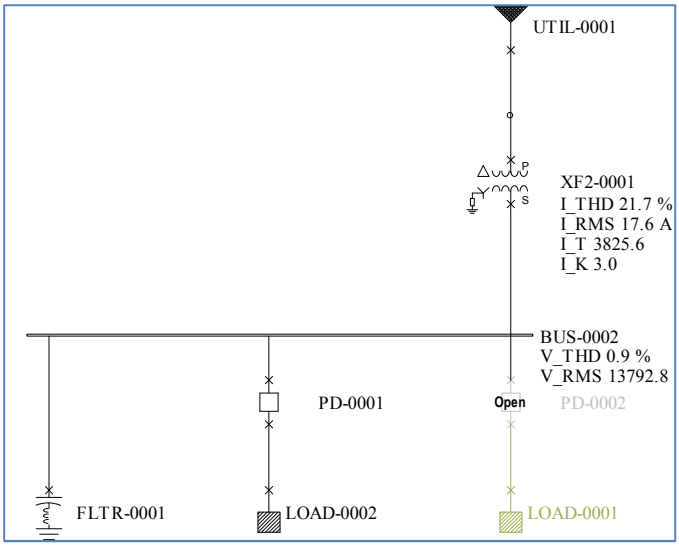

Figure 29: Case 5- Harmonic load flow at the 13.8 kV bus

From the above case studies, it is clear that adding as low as a 10% nonlinear load to a system that is resonant at a critical point will lead to violating the voltage distortion limits while the capacitor bank performance is still acceptable. Hence, a detuned PFC capacitor bank is required all the time regardless of the load's harmonic content. This application will result in meeting the VTHD criterion at the point of common coupling (PCC) as defined in company standards. In addition, a detuned filter eliminates the possibility of attracting harmonics from a neighboring facility, and prevents parallel resonance in case a nonlinear load is added in the future. Measurements and harmonic analysis shall be conducted prior to power factor correction implementation. This is required to properly size the filter bank in terms of reactor ampacity and capacitor ratings. Filter (detuned PFC capacitor bank) shall be detuned to a typical value of 4.2th order. The detuning point could be increased to 4.6th to avoid parallel resonance at the third harmonic (in case measurements showed presence of 3rd harmonic). It is worth mentioning, that in all cases that the filter bank should evaluated based on IEEE 18 criterion as follows:

- Capacitor operating voltage, current and kvar shall not exceed 100 % of respective rated values under normal system operation.
- Capacitor operating voltage, current and kvar shall not exceed 110 % of rated voltage, 135% of rated current and 135% of rated kVA respectively under system contingency operation.
- Reactor rated current shall be based on calculated total filter current including harmonics [6].

V. CONCLUSIONS

Implementation of power factor to existing facilities requires careful technical and economic analysis. The economic analysis should go beyond straightforward payback calculations. The investment decision should be based on Net Present Value calculations. Furthermore, from technical standpoint, the analysis should entail conducting baseline power quality measurements to estimate the harmonics in the system prior to implementing power factor correction capacitor banks. Specifying a detuning reactor might be worthwhile, even with as low as 10% harmonic load. This will greatly enhance the system immunity against resonance in case future nonlinear loads are added to the system.

VI. REFERENCES

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[4] *C. L. Cooper, R. O. Pragale and T. J. Dionise, "A Systematic Approach for Medium-Voltage Power Factor Correction Design," IEEE Transactions on Industry Applications, vol. 49, no. 3, pp. 1034-1055, 2013.*

[5] *IEEE Std 1036 - Guide for Application of Shunt Power Capacitors, 2010*

[6] *IEEE Std 18- IEEE Standard for Shunt Power Capacitors, 2012, pp.5.*

VII. VITA

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ATTACHMENT A

POWER DATA AND UTILITY CHARGES FORECAST

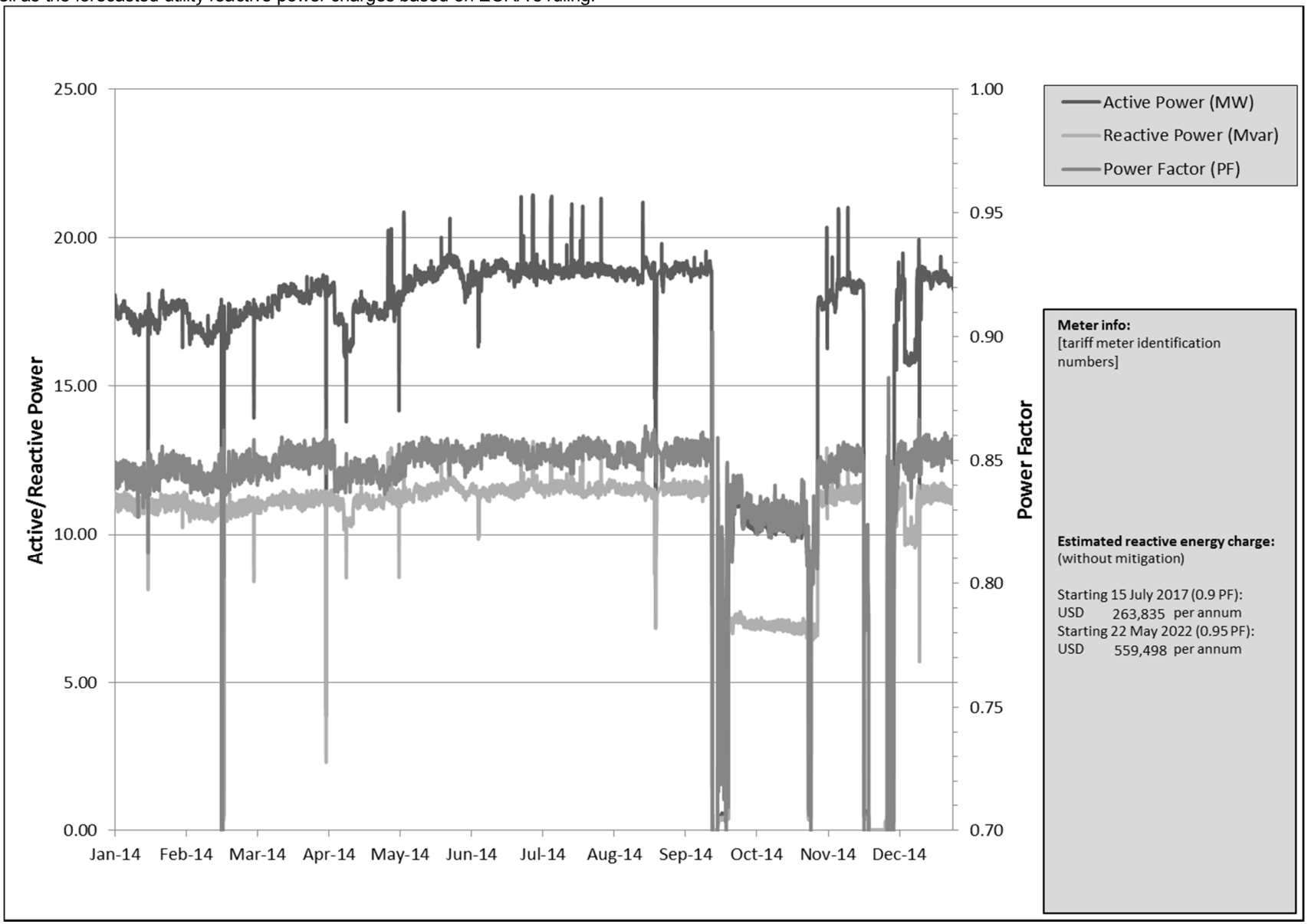
The utility reactive power charges for sites with *monthly* meter readings by the public grid operator SEC were forecasted based on the following formula:

$$A_{monthly\ metering} = \begin{cases} 0, & \sum_{N=1}^{24D} Q_{N,consumption} \leq \sum_{N=1}^{24D} P_{N,consumption} \tan\cos^{-1} PF_{limit} \\ \sum_{N=1}^{24D} (Q_{N,consumption} - P_{N,consumption} \tan\cos^{-1} PF_{limit})T, & \sum_{N=1}^{24D} Q_{N,consumption} > \sum_{N=1}^{24D} P_{N,consumption} \tan\cos^{-1} PF_{limit} \end{cases} [SAR]$$

$D = days\ in\ month$
$P_{N,consumption} = active\ energy\ consumed\ in\ hour\ N\ [kWh]$
$Q_{N,consumption} = reactive\ energy\ consumed\ in\ hour\ N\ [kvarh]$
$PF_{limit} = power\ factor\ treshold\ as\ stipulated\ by\ ECRA\ Decision\ No.\ 2/27/33$
$T = tariff\ reactive\ energy\ as\ stipulated\ by\ ECRA\ Decision\ No.\ 2/27/33\ = 0.05\ [\frac{SAR}{kvarh}]$

Whereas the utility reactive power charges for sites with *hourly* meter readings by SEC were forecasted based on the following formula:

$$A_{hourly\ metering} = \sum_{N=1}^{24D} Q_{N,deficit}\, T[SAR]$$

$$Q_{N,deficit} = \begin{cases} 0, & Q_{N,consumption} \leq P_{N,consumption} \tan\cos^{-1} PF_{limit} \\ Q_{N,consumption} - P_{N,consumption} \tan\cos^{-1} PF_{limit}, & Q_{N,consumption} > P_{N,consumption} \tan\cos^{-1} PF_{limit} \end{cases} [kvarh]$$

Graphical representations (charts) were created for all relevant company facilities reflecting the active and reactive energy consumption for a representative year as well as the forecasted utility reactive power charges based on ECRA's ruling.