Assessment of MVAR Injection in Power Optimization for a Hydrocarbon Industrial Plant Using a Genetic Algorithm

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Abstract- **In this paper, a genetic algorithm (GA) is considered for assessing the effect of Million Volt-Ampere Reactive (MVAR) power injection via shunt capacitors in optimizing the electrical power loss for a real hydrocarbon industrial plant. The subject plant electrical system consists of 275 buses, two gas turbine generators, two steam turbine generators, large synchronous motors, and other rotational and static loads. The minimization of power losses objective is used to guide the optimization process, and, consequently, the injected power in the grid is monitored. First, the optimal locations of MVAR injection will be identified using a voltage stability index. The potential of power loss optimization with and without MVAR injection versus the base case will be discussed in the results. The results obtained demonstrate the potential and effectiveness of the proposed approach to optimize the power consumption in both scenarios (with and without MVAR injection). Also, in this paper a cost appraisal for the potential daily, monthly and annual cost saving in both scenarios will be addressed.**

Keywords-**genetic algorithm**, ***power loss optimization, electrical submersible pump, hydrocarbon facility, British thermal unit (BTU), millions of standard cubical feet of gas (MMscf).***

I. INTRODUCTION

Since 2009, an environment of urgency was created to deal with the exponential increase of the domestic energy used in the kingdom of Saudi Arabia. All stockholders since then are working together in many initiatives sponsored by the government of the kingdom to address the optimization and the efficiency improvement of energy in all utility sectors, especially, the electrical generation sector. The kingdom international commitment to reduce the CO_2 emission was another driver for energy optimization in the kingdom. Optimizing the oil usage for electrical generation is also for the benefits of the oil producing countries. The optimization of the energy sector will support the development of downstream petrochemical industries and other very promising industries. In addition, the need of shaping the high annual rate increase of energy demand becomes a major concern for most of the developing countries. For example, in Saudi Arabia, the annual electric demand increase is around 8% [1]. All these pressing critical issues push many countries to develop nationwide strategies for enhancing the electricity generation efficiency, reduce loss and invest in the renewable energy development.

In light of the aforementioned challenges and others, GA was addressed in literature for optimizing the electrical power

system loss. Optimizing the power loss of virtual IEEE system models, improving the performance of the GA by adapting different crossover and mutation techniques and creating a hybrid GA by combining it with other techniques, such as the swarm particles and Fuzzy logic, were among the many techniques addressed in literature. None of the previous studies addressed the application of GA in optimizing the power loss of real h hydrocarbon facility with small system footprint, shorter lines, large machines, combined cycle's generation and large load. [2]-[9].

Generally, there are three approaches to solve the real power loss optimization problem by optimizing the reactive power flow. The first approach applies sensitivity analysis and gradient-based optimization algorithms by linearizing the objective function and the system constrains around operating points [10]. The gradient-based methods are usually subjected to be trapped in local minima which makes the obtained solution not optimal. Moreover, sensitivity factors calculation is a time consuming process. The second approach uses a nonlinear programming technique [11]. This approach has many disadvantages such as long execution time, insecure convergence properties and algorithmic complexity. The third approach utilizes heuristic methods to search the solution space for the optimal solution. This approach is promising as it can overcome the possibility of trapping in local minima [9].

This paper considers an existing real life hydrocarbon central processing facility electrical power system model for assessing the potential of system loss minimization using the GA for two scenarios: without and with MVAR injection. In section 2 of the paper the problem will be formulated as optimization problem with equality and inequality constrains. Also, the voltage stability index will be introduced. In section 3, the GA will be employed to solve this problem. In section 4, the paper study scenarios will be developed. Finally, in section 5 the results technically and economically will be evaluated.

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II. PROBLEM FORMULATION

The problem formulation consists of three parts: the development of the objective functions, the identification of the system electrical constrains to be met; equality and inequality constrains; and the calculation of all load buses stability index (L-Index).

A. Problem Objective Functions

The objective function is to minimize the real power loss J_1 (P_{Loss}) in the transmission and distribution lines. This objective function can be expressed in term of the power follow loss between two buses *i* and *j* as follows:

$$J_1 = P_{Loss} = \sum_{k=1}^{nl} g_k \,[\, V_i^2 + V_j^2 - 2\; V_i V_j \cos(\delta_i - \delta_i)] \qquad (1)$$

Where *nl* is the number of transmission and distribution lines; g_k is the conductance of the k^{th} line, $V_i \angle\delta_i$ and $V_j \angle\delta_j$ are the voltage at end buses *i* and *j* of the k^{th} line, respectively [12] [13].

The real power injected (PR_{Inject}) in the utility grid at Bus# 1 was monitored as J_1 evolves. It is expected that PR_{Inject} will be maximized since it is inversely proportional to J_1; a decrease in the J_1 results in an increase in PR_{Inject}.

B. Problem Equality and Inequality Constrains

The system constrains are divided into two categories: equality constrains and inequality constrains [9][13]. Details are as follows:

B.1 Equality Constrains

These constrains represent the power load flow equations. The balance between the active power injected P_{Gi}, the active power demand P_{Di} and the active power loss P_{li} at any bus i is equal to zero. The same balance apply for the reactive power Q_{Gi}, Q_{Di} , and Q_{li}. These balances are presented as follows:

$$P_{Gi} - P_{Di} - P_{li} = 0 \qquad (2)$$

$$Q_{Gi} - Q_{Di} - Q_{li} = 0 \qquad (3)$$

The above equations cane be detailed as follow:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{NB} V_j \,[\, G_{ij} cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] = 0 \qquad (4)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{NB} V_j \,[\, G_{ij} sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] = 0 \qquad (5)$$

where i = 1,2,…,NB;NB is the number of buses; P_G and Q_G are the generator real and reactive power, respectively; P_D and Q_D are the load real and reactive power, respectively; G_{ij} and B_{ij} are the conductance and susceptance between bus i and bus j, respectively.

B.2 Inequality Constrains

These constrains represent the system operating constrains posted in Table III and they are as follow:

a. Generator and synchronous motor voltages; V_G and V_{Synch}; their reactive power outputs; Q_G and Q_{Synch}.
b. The transformers taps.
c. The load buses voltages V_L.

Combining the objective function and these constrains, the problem can be mathematically formulated as a nonlinear constrained single objective optimization problem as follows:

Minimize J_1
Subject to:

$$g(x,u) = 0 \qquad (6)$$

$$|h(x,u)| \le 0 \qquad (7)$$

where:

x: is the vector of dependent variables consisting of load bus voltage V_L, generator reactive power outputs Q_G and the Synchronous motors reactive Power Q_{Synch}. As a result, x can be expressed as

$$x^T = [V_{L1}..V_{LNL}, Q_{Gi}\ldots Q_{GNG}, Q_{Synchi}\ldots Q_{SynchNSynch}] \qquad (6)$$

u: is the vector of control variables consisting of generator voltages V_G, transformer tap settings T, and synchronous motors voltage V_{Synch}. As a result, u can be expressed as

$$u^T = [V_{G1}..V_{GNL}, \quad T_1\ldots T_{NT}, \quad V_{Synch1}..V_{SynchNL}] \qquad (8)$$

g: are the equality constrains.
h: are the inequality constrains.

C. Voltage Stability Index (L-Index)

The *L* indicator varies in the range between 0 (the no load case) and 1, which corresponds to voltage collapse. This indicator uses the bus voltage and network information provided by the power flow program to measure the stability of the system. The *L* indicator can be calculated as given in [14]. For a multi-node system

$$I_{bus} = Y_{bus} \times V_{bus} \qquad (9)$$

By segregating the load buses (PQ) from generator buses (PV), (8) can be written as:

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} H_1 & H_2 \\ H_3 & H_4 \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (11)$$

where
V_L , I_L *are load buses voltages and currents*
V_G , I_G *are Generator buses voltages and currents*
H_1 ,H_2 ,H_3 ,H_4 *are submatrices generated from* Y_{bus} *Partial Inversion*
Z_{LL} ,F_{LG} , K_{GL} ,Y_{GG} *are submatrices of H-matrix*

Therefore, a local indicator L_j can be worked out for each node j similar to the line model

$$L_j = \left| \mathbf{1} - \frac{\sum_{i \in \alpha G} F_{ji} V_i}{V_j} \right| \quad (12)$$

For a stable situation the condition $L_j \leq 1$ must not be violated for any of the nodes j. Hence, a global indicator L describing the stability of the whole system is given by:

$$L_{max} = \text{MAX}_{j \in \alpha L} \left| \mathbf{1} - \frac{\sum_{i \in \alpha G} F_{ji} V_i}{V_j} \right| \quad (13)$$

where α_L is the set of load buses and α_G is the set of generator buses.

III. THE PROPOSED APPROACH

A. Electrical System Model Data Collection

The research electrical models system parameters were gathered and categorized in tables to be ready for developing the simulation model of the system. The gathered parameters include the followings:

a. Generators type, voltage and capacity, including active and reactive capacity curves reflecting the operation limitations such as stator and rotor thermal limitations.
b. The Generators BTU/kW equation and cost equation.
c. Utility power system parameters (swing bus); bus voltage and short circuit MVA.
d. System buses voltage constrains.
e. Lines parameters, including the lines resistance, reactance, capacitance, length and voltage.
f. Transformers parameters including primary voltage, secondary voltage, voltage taps, size and impedance.
g. The large synchronous motor parameters, including active and reactive power curve reflecting the operation limitations such as stator and rotor thermal limitations.
h. The large induction motor and the electrical submersible pumps (ESPs) parameters such as the active and reactive power demands.
i. The lumped load Thousand Voltage-Ampere (KVA) rating. All loads except the motor rated > 5000 Horse Power (HP) and the ESP are modeled as lumped load.

B. Optimal Locations of the Shunt Capacitors

The L index described in (13) was employed to identify the most sensitive load buses with regard to voltage stability. These most sensitive load buses were selected for shunt capacitors connection.

C. Generic Algorithm Implementation

The implementation of the developed GA technique can be summarized in the following steps:

1) Generate initial populations of chromosomes; each chromosome consists of genes and each of these genes represents either transformer tap settings, synchronous motors voltages, the generators voltages or shunt capacitors MVAR values.
2) Assign fitness to each chromosomes as follows;
   a. Use the Newton-Raphson method to calculate the real power losses for each population [15].
   b. Identify if the voltage constrains are satisfied.
   c. Identify if the Synchronous machines (generators and motors) capacity limitations are met.
   d. Assign fitness values to the populations that meet the voltage constrains; the population best power loss value (J_1) divided by the base case power loss value.
   e. Assign penalty values to those populations that do not meet the voltage constrains; constant value (0.05).
3) Identify the best population with its associated chromosomes that has the best objective function value and store it.
4) Identify the chromosomes parents that will go to the mating pool for producing the next generation via the Random Selection method. This method works by generating two random integer numbers (each represents a chromosome). Then, these two randomly selected chromosomes fitness values are compared and the one with the better fitness value will go into the mating pool. This randomly selected chromosomes mechanism will be repeated until the population in the mating pool equals to the initial chromosomes population [16].
5) Perform genes crossover for the mating pool parents via the Simple Crossover method [16]. In this method, the offspring chromosomes are generated by establishing a vertical crossover position for parent's chromosomes and then crossover their genes.
6) Perform gene mutation for the mating pool parents after they have been crossed over; the Random Mutation method was implemented [16]. In this method, the offspring chromosomes genes are mutated to new ones randomly from the genes domain.

7) Go to Step #2 and repeat the above steps with the new populations generated from the original chromosome parents after being crossed over and mutated.
8) Each time, identify the best population and compare its fitness value with the stored one; if it is better (meeting the objective function), replace the best chromosomes with the new ones.
9) The loop of generation is repeated until the best population with its associated chromosomes, in terms of minimum real power loss, is identified or the maximum number of generations is met. The flow chart of the proposed approach implemented is shown in Figure 1.

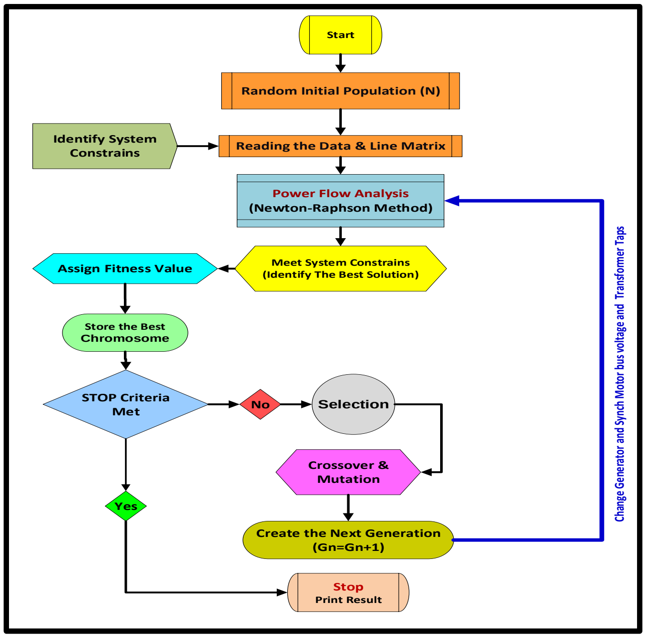

Figure 1. The GA algorithm evolution process flowchart

IV. Study Scenarios

In this paper, three scenarios were studied: the base case scenario (system as usual), the optimal case scenario without MVAR injection, and the optimal case scenario with MVAR injection. In the optimal cases the best system parameters (chromosomes) that meet the minimum objective function (J_1) are obtained.

A. Base Case Scenario

Normal system operation mode was simulated to be benchmarked with the two optimal scenarios. Following are some of the normal system operation mode parameters:

1) The utility bus and generators terminal buses were set at unity p.u. voltage.
2) All the synchronous motors were set to operate very close to the unity power factor.
3) All downstream distribution transformers and the captive synchronous motors transformers; off-load tap changers; were put on the neutral tap.
4) The causeway substations main transformers taps were raised to meet the very conservative voltage constrains at these substations downstream buses; ≥ 0.95 p.u. Refer to Table I below.

TABLE I
THE SELECTED FEASIBLE TRANSFORMERS TAPS VALUE

Substation Number	Transformer Tap
Causeway Substation#1	+3 (1.019 p.u.)
Causeway Substation#2	Neutral (1.0 p.u.)
Causeway Substation#3	+3 (1.019 p.u.)
Main Substation Transformers	+1 (1.006 p.u.)

B. Optimal Case Scenario without MVAR injection

To optimize the elevation process time the unfeasible transformers tap values (genes) were not selected. In other words, the genes values were limited to certain taps around the neutral taps out of the all taps full range; ±16 taps. Table II below posts the selected range of the transformers tap values and the percentage of the voltage change for each tap.

TABLE II
THE SELECTED TRANSFORMER TAP FEASIBLE GENES VALUE

Description	Upper Tap	Lower Tap
Main Transformers	+8 (0.625%)	-4 (0.625%)
Causeway Main Transformers	+8 (0.625%)	-3 (0.625%)
Captive Motors/Distribution Transformers	+1 (2.5%)	-1 (2.5%)
Generator Step-up Transformers	+5 (1.25%)	-4 (1.25%)

An initial 200 populations of feasible chromosomes (individuals) which meet both the buses voltage and synchronous machine reactive power constrains were identified. These feasible populations are associated with the first optimal scenario; without MVAR injection. The feasible populations with their associated chromosomes were subject to the GA evolutionary process of 20 generations guided by the objective function J_1. The $\boldsymbol{PR_{Inject}}$ was monitored as J_1 evolved. The GA process was set with 90% crossover probability and 10% mutation probability. The system parameters and the objective function value associated with the optimal solution of this scenario were identified.

C. Optimal Case Scenario with MVAR injection

The evolutionary process was optimized via the same method employed in the second case scenario. Another initial 300 populations of feasible individuals were identified in for the second optimal scenario; with MVAR injection. In this scenario, MVAR shunt capacitors are connected to the preselected buses; refer to Table IV. In this case, the MVAR chromosomes are extended to include MVAR injection considered as control variables. The feasible populations with their associated chromosomes were subject to 20 generation of GA evolutionary process. The crossover and

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mutation probability were set equal to those in the scenario without MVAR injection: 90% and 10%, respectively.

V. RESULTS AND DISCUSSIONS

The results from the three scenarios, base case, without MVAR injection and with MVAR injection, will be analyzed in two categories: the system parameters analysis and the economic analysis.

A. System Parameters Analysis

The hydrocarbon facility simplified electrical system model, which is studied in this paper, is shown in Figure 2.

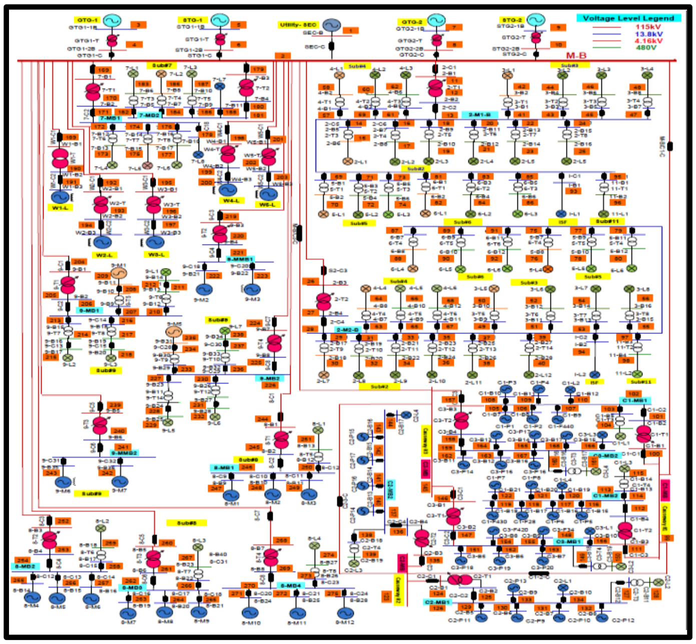

Figure 2. Simplified electrical system of the hydrocarbon processing facilty

The system inequality constrains are posted in Table III.

TABLE III
SYSTEM INEQUALITY CONSTRAINS

Description	Lower Limit	Upper Limit
GTG Terminal Voltage (V_{GTG})	90%	105%
STG Terminal Voltage (V_{STG})	90%	105%
GTG Reactive Power (Q_{GTG}) Limit	-62.123 MVAR	95.72 MVAR
STG-1 Reactive Power (Q_{STG}) Limit	-22.4 MVAR	20.92 MVAR
STG-2 Reactive Power (Q_{STG}) Limit	-41.9 MVAR	53.837 MVAR
Captive Synch. Motors Terminal Voltage	90%	105%
Synch. Motors Terminal Voltage (V_{Sychn})	90%	105%
Causeway downstream Buses Voltage	95%	105%
All Load Buses Voltage	90%	105%
Main Transformer Taps	+16 (+10%)	-16 (-10%)
Generators Step-Up Transformer Taps	+8 (+10%)	-8 (-10%)

Base on the substation load buses stability index rank, the selected buses for shunt capacitors connection, together with the potential MVAR values, are posted in Table IV.

TABLE IV
THE SELECTED BUSES FOR MVAR INJECTION

Substation Number	Bus Number	Potential MVAR
Substation#2	13 and 28	[8 8.5 9 9.5 10]
Causeway Substation#1	102 and 113	[1.5 2 2.5 3 3.5]
Causeway Substation#2	124 and 137	[2 2.5 3]
Causeway Substation#3	148 and159	[2 2.5 3]

The evolution of the objective function (J_1) and PR_{Inject} values over the GA process is captured in Figure 3. The benchmark for the system real power loss and the injected power in the grid is demonstrated in Figure 4. There are 0.202 Million Watts (MW) and 0.203 MW reduction in the system loss between the base case, the no MVAR and with MVAR optimal cases sequentially. The same amount of MW were injected in the grid for both scenarios.

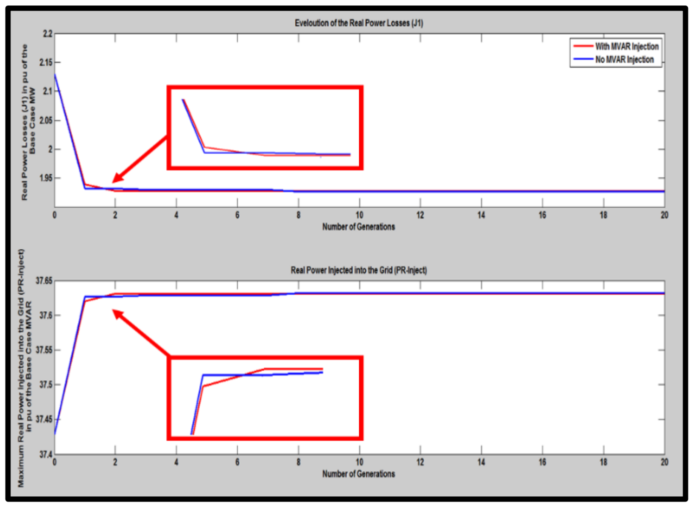

Figure 3. J_1 and PR_{Inject} value convergent for 10 generations

The system for the two optimal cases demonstrates an improvement in the system buses p.u. voltage profile, which increases the robustness of the system (Figure 5).

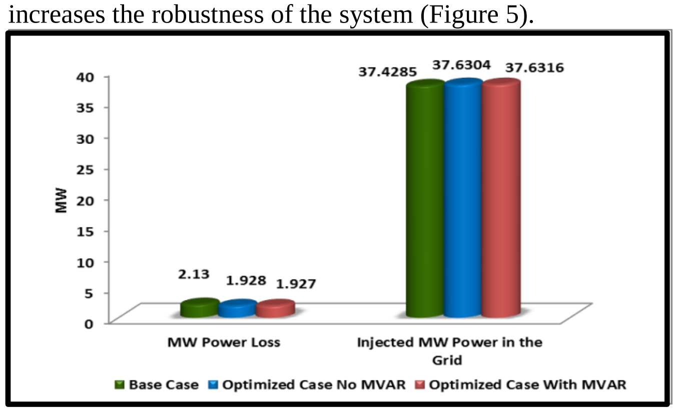

Figure 4. System power loss and injected power benchmark

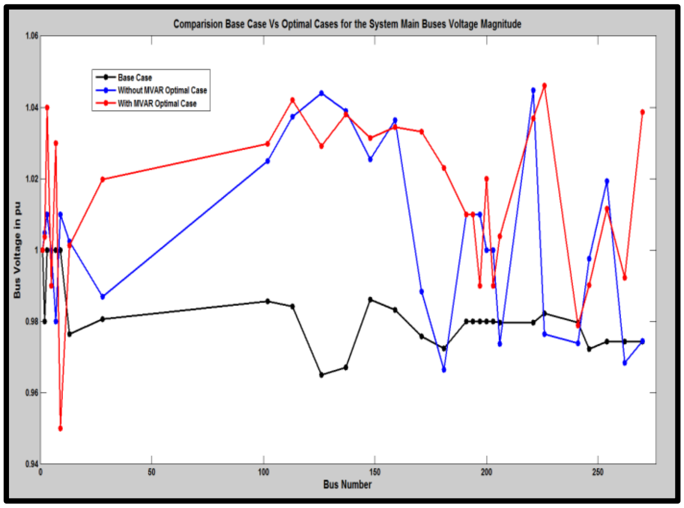

Figure 5. The main system buses' voltage benchmark

The paper shows there is not much power loss reduction associated with MVAR injection scenario compared to the no MVAR injection scenario [17] due to the system stiffness and its small footprint.

B. Economic Analysis

The avoided cost due to the optimization of the system power loss is demonstrated in Figure 6 at daily, monthly and annual bases. The annual cost avoidance based on natural gas cost of $3.5 per MMscf is around $60,300/year and $60,400/year for the no MVAR and with MVAR optimal cases sequentially when compared to the base case.

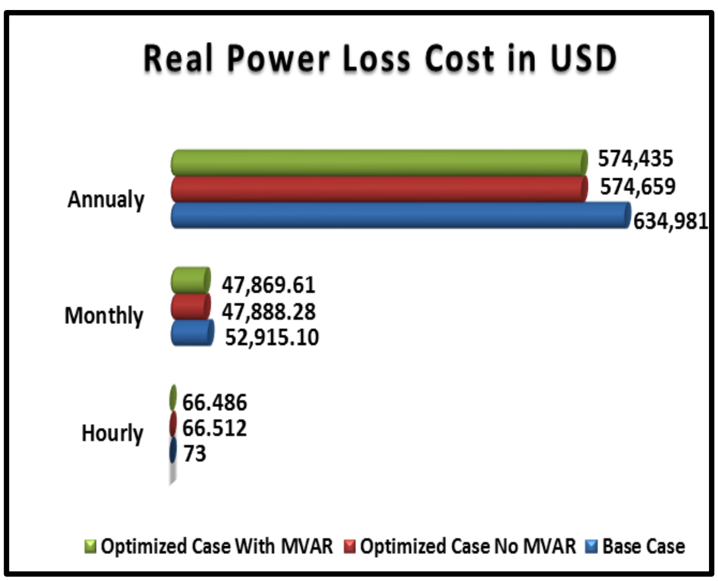

Figure 6. The system power loss cost

The revenue due to the power injection in the grid at both scenarios is shown in Figure 7.

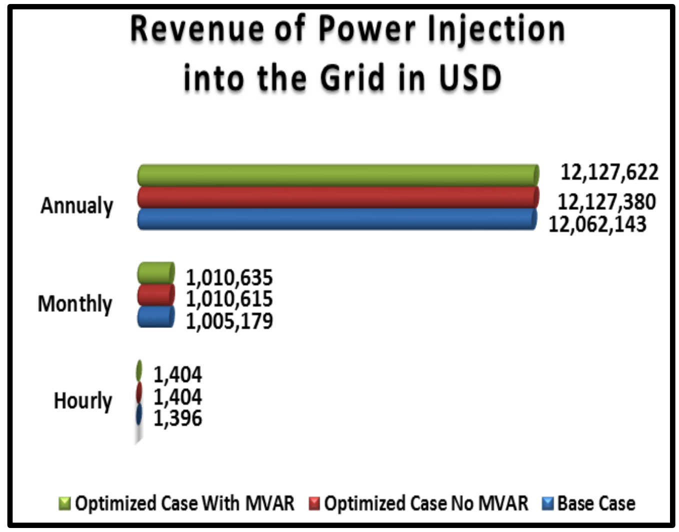

Figure 7. Revenue due to power injection in the grid

The figure illustrates the potential of the optimal scenarios in increasing the revenue using $37.3 MWh tariff rate; $65,200/year for the no MVAR optimal case and $65,500/year for the with MVAR optimal case benchmarked to the base case.

VI. CONCLUSION AND FUTURE WORK

This paper presented the potential of minimizing the power system loss for a real-life hydrocarbon facility using the GA base approach considering no MVAR and with MVAR injection scenarios. Consequently, the increase in the injected power to the grid due to the loss optimization was also captured. The paper demonstrated that the reduction of power loss associated with MVAR injection is minimum. The economic advantages of the optimal scenarios modes versus the base mode were highlighted in this paper. The economic advantages of the with MVAR injection scenario compared to the no MVAR scenario did not support the shunt capacitor installations as the advantages are minimal. Improvement to the system buses voltage profile was shown to be a byproduct of the system power loss optimization. Future study may need to address the effectiveness of different selection, crossover and mutation methods in optimizing the system loss through GA evolutionary process.

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