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Studying the Influence of Connecting New Energy Saving Loads on the Electrical Power System of Nuclear Facility

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ABSTRACT

Electrical system of nuclear facility should have suitable safety mechanisms and minimum losses for providing reliability of power supply to guarantee the continuity of operation. The purpose of having electrical infrastructure with high efficiency is to have energy delivery systems with high efficiency. So in this research, a proposed model of the nuclear reactor electrical system will be presented to study the effect of connecting new energy saving loads and advanced controllers on the system performance in order to keep safe and good performance of this nuclear facility. By using Electrical Transient Analysis Program (ETAP) software the NRR simulation model was developed. The analysis was performed with using nonlinear energy saving lighting systems and Variable Frequency Drive (VFD) installed as a controlled for secondary pump of the reactor by providing smooth motor starting also its advantage for energy saving. From the results, active power consumed and current were reduced, while VTHD and ITHD increase clearly. Finally the influences of using large number of LED (Light Emitting Diode) lamps and VFDs on the power quality were observed but not exceed the IEEE standard limits. Also, its impact on energy savings and economic benefits with safe and reliable operation was achieved.

1. Introduction

The main objectives of energy saving technologies are declining the consumption of power while standby operation and changing the power source from pneumatic or hydraulic to electromagnetic drive systems, controlled by electronics. There are a lot of energy saving technologies one of them electric motors with energy-efficient which reduce energy losses and improve manufacturing techniques. The electric motors are joined with suitable inverters to control its speed and maintained at the most efficient condition to save energy. An Uninterruptible Power Supply (UPS) is considering another type of energy saving technologies. UPS is an electrical machine that provides emergency power to run when the input power supply system’s interrupted and used to protect hardware such as telecommunication equipment, data centers, computers or any electrical equipment where an unexpected power interruption could cause data loss. Also Soft starters provides an economical and reliable solution to the problems like excessive wear and premature failure of chains, belts, gears, mechanical seals, etc. by providing a

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controlled run of power to the motor, thereby giving smooth, step less acceleration and deceleration. Damaging of bearings and windings is reduced so motor life will be extended [1].

Variable speed drives, also one of the energy saving techniques; gradually rise the motor speed to operating speed to reduce electrical and mechanical stress, decreasing repair and maintenance costs, and extending the motor lifespan. variable frequency drive is used to control the device being connected by making the starting of motor smoothly also its advantage for energy saving and achieving high system efficiency, increase the heat of device component which considered the losses during process of frequency conversion which causes the harmonic distortion in the network [2-4].Also there is a major possible for electricity saving and reducing energy costs of consumer during the use of air-conditioning with high efficiency and lighting technologies [5].

LED replacements can be used instead of conventional lighting which have less power consuming and produce better illumination. Thus, LED lighting system is used more other conventional lighting systems like high pressure sodium, incandescent, metal halide, fluorescent, etc. Thus it is recommended that LED lighting system should use instead of usual conventional lighting systems [6-8].Beside the advantages of using LED lamps of energy consumption, there have negative effect on both the utility and consumer side which observed through different power quality problems [9-11]. In references [12-14] LEDs are the causes of harmonics as electronic circuits used through their firing. These harmonic sources have badly effect on other loads connected to the same bus. It also make distortion in current and increase reactive power (reduction in power factor), which overall called poor power quality. LEDs lighting installations generate reactive power which caused power loss and reduction of the efficiency of the grid. Compensating of the reactive power can be attained by connecting extra inductors in lighting control cabinets [15].

Operation of high-performance LED light sources with large number of power electronic converters leads to increase in reactive power flow which related to transmission losses of electrical energy and producing of higher harmonics[16].LEDs lights are non-linear loads producing high frequency current harmonics, which can caused PQ problems, increased power losses of cables and transformers, aging of induction motors and malfunction of communication system so the recommendations for the using of LED lights will be given to achieve expected efficient-energy system[17].

Electrical power supply system has its important effect on safety of nuclear facility, so that, it’s important to study the availability of reliable electrical power supply to ensure reliable and safe operation of nuclear facility. Many of the International Atomic Energy Agency (IAEA) publications study electrical power supply systems and its effect on safety for essential functions of nuclear facilities such as communications systems and nuclear reactor protection. Additionally, give guidance to design a reliable emergency electrical power supply system [18-20].

The electrical power disturbances such as vibration, overheating, noise, damage of motor windings, overloads on the distribution network, types of lamps burning out, malfunction and failure of some sensitive equipment, overloads on the distribution network, failures in transformers at low loads .These problems affect the safety of the facility which, increasing the operating costs, decreasing lifespan of component and reflecting power quality problems in the facility [19].

The main two types of Nuclear Reactors (Power and research) are containing safety related auxiliary systems. Those systems have a lot of critical loads which need electrical power for most or all safety functions. So Nuclear Reactors are normally required by their operating license to have multiple sources of electricity, including a minimum of two independent offsite power sources and onsite power sources which should be with high reliability, stability and power quality.

In this paper, a nuclear research reactor NRR is selected to be the case study for power quality evaluation. The paper discusses the effect of the existence of nonlinear loads on power quality by developing a model of NRR electrical system to investigate the problems that may face the reactor operators while simulating different operating conditions. Proposed model will be represented to improve the electrical system performance and efficiency through renewing some of its electrical components. In this case, the new equipment will be modern and energy saving ones. A study of the proposed state after replacing lighting systems with nonlinear energy saving lighting systems which is in fact, based on Light Emitting Diodes (LEDs) and installed VFD as a controlled for secondary pump of the research reactor will be presented. The effect of nonlinear loads with additional nonlinear energy saving lighting loads on the power quality (PQ) and the operation will be studied and analyzed to recommend the optimum case after make technical and economic analysis.

2. Proposed Case Study Description and Modeling

In nuclear facilities, one of the most important systems is electric power supply system. Its safety function is to achieve required power of appropriate quality of equipment and other systems to ensure their ability to achieve their required safety functions. Generally, the electric power supply system of the NR has been designed to meet the following general requirements:

- Demands for startup, operation, and safe shutdown.
- Simple bus arrangement
- Flexibility of operation - Easy & safe switching manoeuvring
- Possibility of system expansion
- Ease of maintenance
- Withstanding abnormal conditions (short circuit, overcurrent, under/over voltage, transients, etc.)

2.1. General description of the NRR Electric Power Supply system

In view of increasing the reliability and availability of the system, electric power is supplied as from different sources, which are undependable. Independence of components and circuits can be achieved by physical separation or electrical isolation. So that any single failure affects only one source of supply and does not propagate to other sources. Specifically, electric power supplies of the NRR under study are divided into three types:

- Class "A" - Uninterruptible Power Supply: Uninterruptible Power Systems UPSs (on-site and near to the supplied load). Feed power to loads of relevant equipment without interruption in time from the cut-off of the main source until the connection of the essential source
- Class "B" - Essential power supply: Standby Diesel Generator sets (on-site). Feeds essential plant's services during a main power cut-off.
- Class "C" - Main (normal) power supply: Utility 11kV lines (off-site). Feed power all the time to start-up the plant and manage the electricity demand as a whole.

In case of supply interruption from the external lines (class C supply) and until the onsite power plant (class B supply) starts supplying energy, electrical loads requiring uninterruptible power (i.e., class A loads) are fed from an uninterruptible power system (class A supply).

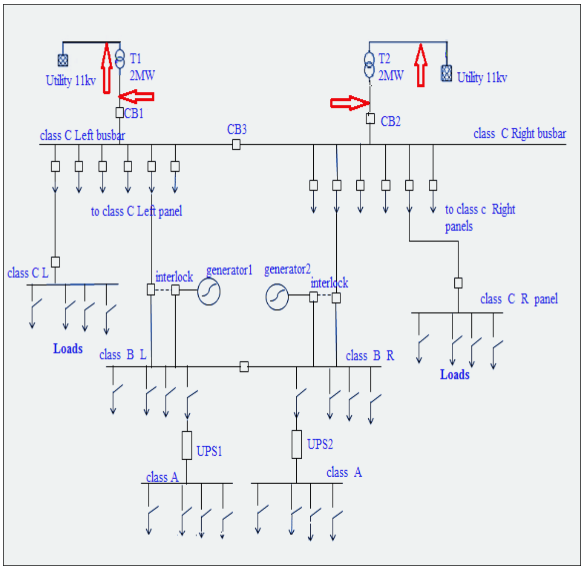


Fig.1: Single line diagram of NRR Electrical System

The NRR model was performed by using ETAP ver.12.6 software. The load flow analysis and the harmonic analysis were performed. The data and analysis were performed according to the basic design of NRR electrical systems. The purpose of performing the load flow analysis was to calculate currents, branch power factors, bus voltage, and power flows of electrical system. It's common that, using nonlinear energy saving lighting systems, which is in fact, based on Light Emitting Diodes (LEDs) will cause major disturbances in the electric distribution networks. These disturbances are cause poor power quality including the effects of harmonics present in the current and voltage of the network. Also the main defying in used VFDs applications is losses in its component in the form of heat generated throughout the process of frequency conversion which lead to harmonics in the electrical system. The harmonic analysis was conducted to determine its effects on the buses specific and main transformer in case of LEDs and VFDs controller were connected.

3. Simulation the Influence of Lighting System

Industrial facilities are searching for the best methods to reduce the costs of power consumptions during the generation. Thus, this paper focuses on replacement of conventional lighting with LEDs lighting with the similar luminous flux as a first method of energy saving in the facility. Investigating when used the LEDs lamps in the system if there are any significant advantages in energy and cost saving or not. Table 1 shows the parameters of the lighting loads.

The selection of lighting system based on one of two cases:

a) NRR loads with conventional lights (incandescent lamps +fluorescent lamps + high pressure sodium lamps) in the first case,

b) NRR loads with energy saving lights with the same luminance power as in a (LED lamps) in the second case.

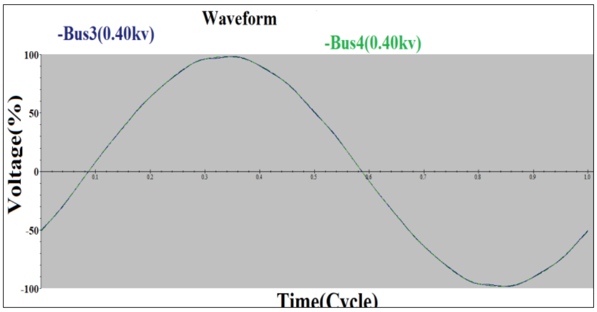
Table 1: Parameters of used lamps

Type of lamps	No. of lamps	Rated power (w)/lamp	Equivalent to LEDs P(w)	Luminous flux(lm)/lamp
Fluorescent lamp(FL)	646	40	18	1600
Incandescent lamp (IL)	86	100	18	1600
	10	75	12	1100
	64	60	10	850
	4	40	7	500
High pressure sodium lamp (HPS)	30	400	150	50000
	2	250	150	28000
	14	160	150	16000

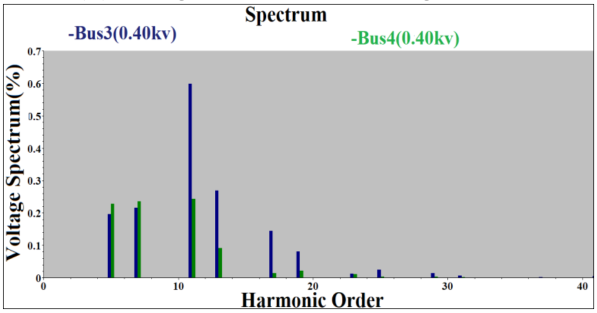
3.1. Case 1: actual connected lighting system loads without energy saving

For the simulations the NRR electrical power system was modelled. The NRR electrical power system is supplied by two independent sources at medium voltage level from two different substations to keep good reliability. Each source feeds a separate transformer through a circuit breaker. Each transformer and its busbar are able to carry the total demand power of the plant as shown in figure 1. The simultaneous operation of conventional lighting was simulated. For this purpose a model of all linear and non-linear loads was designed in the previous work [21].

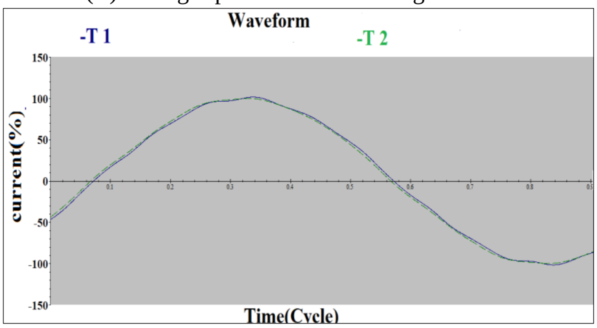
From figure 2 the waveform and spectrum of all connected loads of NRR in the observation points (shown by red arrow in figure 1) are represented. The NRR model represents the combined operation of all loads with incandescent lamps, fluorescent lamps and high pressure sodium lamps.



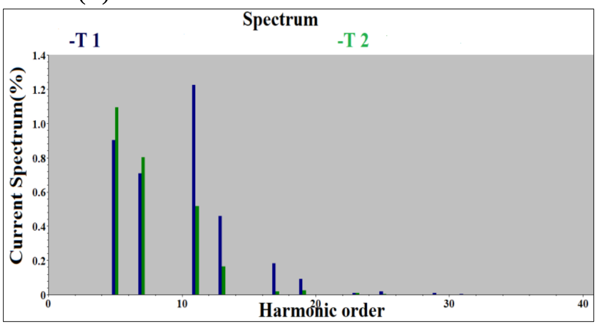
(A) Voltage waveform at low voltage sides



(B) Voltage spectrum at low voltage sides



(C) Current waveform at main transformers

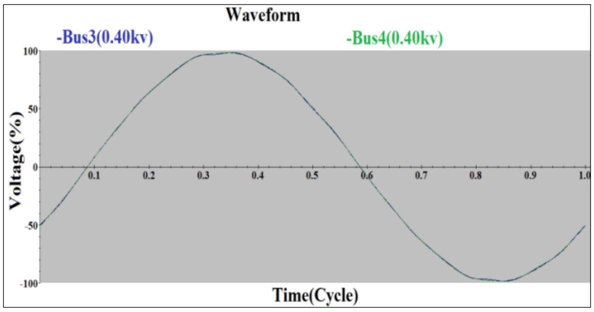


(D) Current spectrum at main transformers

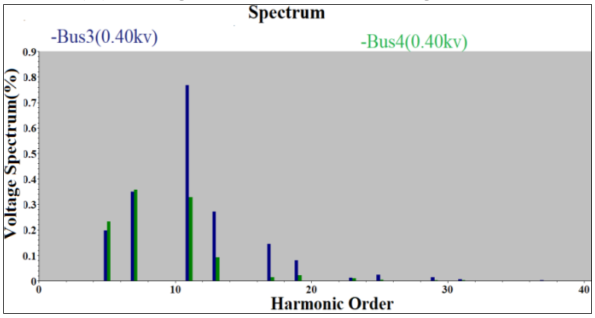
Fig.2 (A, B, C, D): Waveform and Spectrum of voltage and current in the observation points without energy saving

3.2. Case 2: update lighting system with energy saving loads

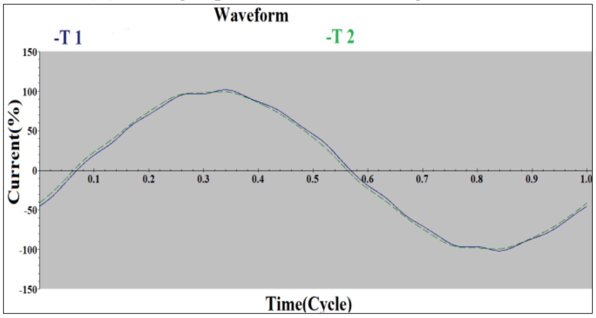
Based on the measurements of currents of LED lamps [22-24], operation of LED lamps with other loads was simulated using ETAP software and Power quality parameters were analysed.



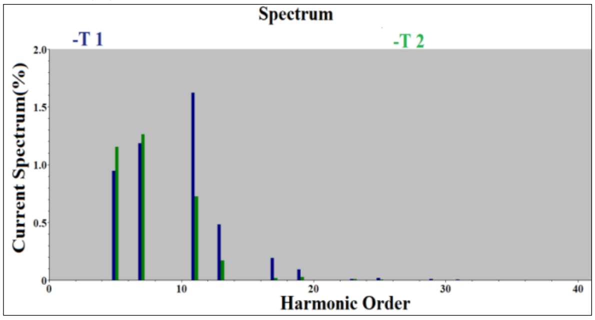
(A) Voltage waveform at low voltage sides



(B) Voltage spectrum at low voltage sides



(C) Current waveform at main transformers



(D) Current spectrum at main transformers

Fig.3 (A, B, C, D): Waveform and Spectrum of voltage and current in the observation points with energy saving Lighting system

3.3. Simulation results

For each case the waveform and spectrum were obtained in the investigation points as shown in figures2, 3. Table 3 shows the reactive power, active power, power factor and current in the grid for each case of lighting load. Table 4shows the total harmonic distortion THD in four observation points – at the medium voltage and low voltage sides of the T1 and T2 transformers. As shown in figure 3, 5^{th}, 7^{th} and 11^{th} are harmonics dominating in the current. Total voltage harmonic distortions (VTHD) is reached to 0.86% and ITHD is 2.07% as shown in table 4, which are relative to many electronic converters used in the NRR.THD limits in both LV and MV sides of network never exceed The IEEE Std 519-2014 standard as shown in table 2[25].

Table 2 —Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0

Table 3: results of two cases

	NRR with lighting (IL+FL+HPS) loads		NRR with lighting (LEDs) loads	
	Utility source 1 (medium-low)	Utility source 2 (medium-low)	Utility source 1	Utility source 2
Active power(KW) (medium-low)	874-868	845-841	854-846	822-818
Reactive power(KVAR)	453-423	412-385	428-399	357-333
Power factor (%)	88.8-89.9	89.9-90.9	89.4-90.5	91.7-92.6
Current(A)	81.64-1420	49.35-1357	50.13-1378	47.07-1294

Table 4: Total harmonic distortions in different positions for two cases of NRR loads

Total voltage harmonic distortion VTHD(%)		
	With (IL+FL+HPS)	With LED
At medium voltage (T1)	0.21	0.24
At medium voltage (T2)	0.12	0.16
At low voltage (T1 end of LV line)	0.75	0.86
At low voltage (T2 end of LV line)	0.43	0.55
Total current harmonic distortion ITHD(%)		
At main transformer (T1)	1.75	2.07

3.4. Energy cost and saving analysis

In this section, the method and the steps carried out explained based on the case study. Electricity consumption cost of electricity consumption, energy saving, energy saving cost and period of payback are described [26].

- Electricity Consumption
  The electricity consumption of the conventional lighting systems and the energy saving lighting systems was

determined by multiplication of the number of units N, power rating W and the operating hours OH.

$$\text{Electricity Consumption (KW)} = \frac{N*W*OH}{1000} \quad (1)$$

- Cost of Electricity Consumption
  Electricity consumption Cost is the multiplication of electricity consumption with the price of electricity per kwh.

  Electricity consumption Cost = electricity consumption* price of electricity (2)

- Energy Saving
  Energy saving is the differences between the energy consumption of existing units and the proposed units.

  $$\text{Energy saving} = \text{electricity consumption}_{\text{Existing}} - \text{electricity consumption}_{\text{Proposed}} \quad (3)$$

- Cost of Energy Saving
  Cost saving was determined by multiplying energy saving with the price of electricity

  Cost saving = energy saving * price of electricity (4)

- Payback Period
  The payback period is defined as the time taken to recover its initial cost from the saving of the cost of energy paid to the electricity company.

  $$\text{Payback period (years)} = \frac{\text{incremental cost(\$)}}{\text{Annual cost of energy saving (\$/year)}} \quad (5)$$

From the view of electricity metering, assuming the IL, FL,HPS and the LED lamp are operate for 1 hour, their energy consumption are explained in Table 5,6. Supposing that the lamps are operate for 25000 hour as the life span of LEDs lamps is 250000 hrs, according to the electricity price of 0.07 $/ kWh as mention in EGYPTIAN ELECTRICITY HOLDING COMPANY Annual Report 2018 ,annual economic consumption of the IL, FL,HPS and LED lamps can be calculated, taking the average life and initial cost into consideration.

Table 5: Elecrticity consumptionand cost of IL, FL,HPS and LED lamp

Type of lamp	IL				FL	HPS		
watts	100	75	60	40	40	400	250	160
Lumans per watt	16	15	15	13	40	125	112	100
Life span(hrs)	1200				20000	12000		
Unit price($)	0.5	0.3	0.2	.1	1	5	4	3
Kwh/ 25000 hrs	2500	1875	1500	1000	1000	10000	6250	4000
electricity Cost($) to operate 25000hrs(0.07/kwh)	175	131	105	70	70	700	437.5	280
Units needed for 25000 hrs	21	21	21	21	2	2	2	2
Cost to buy light bulbs for 25000 hrs	$11	$6	$4	$2	$2	$10	$8	$6
Cost to operate for 25000hrs ($)	186	138	109	72	$72	710	446	286
Number of lamps	86	10	64	4	646	30	2	14
Cost of all lamps($)	15953	1375.5	6988.8	288	46512	21300	891	4004

Table 6: Cost of elecrticity consumptionand of LED lamp

Type of lamp	LED				
lumans	500	850	1100	1600	14000
watts	7	10	12	18	150
Lumans per watt	72	85	92	89	94
Life span(hrs)	25000				
Unit price	$1	$2	$3	$4	$157
Kwh/ 25000 hrs	175	250	300	450	3750
Cost of electricity to operate 25000 hrs(at $0.07/kwh)($)	12	17.5	21	31.5	262.5
Units needed for 25000 hrs	1	1	1	1	1
Cost to buy light bulbs for 25000 hrs	$1	$2	$3	$4	$157
Cost to operate for 25000 hours ($)	13	19.5	24	35.5	419.5
Number of lamps	4	64	10	732	46
Cost of all lamps($)	53	1248	240	25986	19297

From table 3, using of LEDs lighting provide reduction in network real power demand at low voltage about 850kW compared to 868 kW without LEDs.
Energy saving= existing – proposed = (868-850) =18kw (3% saving) according to equation 3
Annual energy saving =kW x OH (considering OH 10 hrs per day)

=18*0.4*24*365 =63072kwh

Annual cost saving =kW * OH *(0.07 $/ kwh) according to equation 4

=63072 *0.07= $ 4415.04

In NRR Cost of all lamps to operate for 25000 hours areas follow:

Incandescent lamps (IL): (15953+1375.5+6988.8+288.4) = $24605.7,

Fluorescent lamps (FL): 646* $72 = $46512 ,

High pressure sodium lamps (HPS): (21300+891+4004) =$ 26195 and

LED lamps: (53+1248+240+25986+19297) =$46824 respectively.

This means that LEDs lamps can save $50488.7 annually.

4. Simulation the Influence of Energy Saving (VFD) Controller

This paper also focuses on installation of VFD in the NRR as a second way of energy consumptions saving in the facility. The secondary pumps specifications are shown in Table 7. In reference [2] the VFD specification data was proposed according to rating capacity and the input power of the secondary pumps as shown in Table 8. After the NRR model was performed, various analyses were carried out such as load flow analysis and harmonic analysis. It's common that, in the VFDs applications the losses dissipated in its components in form of heat during the process of frequency conversion which leads to the harmonics in the network. The effect of harmonic was determined by preceding the harmonic analysis in the buses specific where VFDs were installed and the main transformer.

Table 7: Secondary pump specification

secondary pumps	
Pump motor type	AC induction motor
Operation pumps No.	2
Standby pumps No.	1
MotorVoltage/Phase/ Frequency	0.4 kV/3Phase/50Hz
Motor rated power	223 kw
Pump rated current	400 A
Pump rated speed	1500 RPM
Efficiency at 100%	94.67% at 85 PF
Efficiency at 75%	92.95% at 91.87 PF
Efficiency at 50%	92.95% at 91.87 PF

Table 8: The proposed VFD specification

Component type	Low Voltage VFD data
Phases No.	3
Supply Voltage	0.4kv
Supply frequency	50 HZ
Output voltage	0.4kv
Rating	200 KVA
Power factor	92%
Operating efficiency	95%

In the simulation the VFDs were set on the bypass mode for disabling operation of the VFDs. The loading condition for the secondary pump was set to 91 %. This value was selected due to the load factor obtained from the field data. The results of load flow analysis simulation including motor input power, power factor and current were registered. The VFD bypass switches were off so that to permit the secondary pump to be controlled by the VFDs, and the loading condition for the secondary pump was still set to 91 %. In Load flow analysis Fig.4 was captured during the load flow simulation with the current operating conditions (without VFD). The motor input current and power factor highlighted in yellow colour were recorded. The motor input current of simulation results of 322.6 A and power factor of 92.8%. Fig. 5 displays the load flow simulation results when proposed VFD was installed for controlling the secondary pumps. Also harmonic analysis results are shown in the Table 9 below at bus where the VFD installed and at the main transformer.Total harmonic distortions increased when VFD proposed was connected but didn't exceed The IEEE Standard. As shown in Table 10, the amount of 7 kW (4% saving) can be saved for one secondary pump and a total of 98112 kwh can be saved yearly which cost $6867.84 for used two VFDs to control two secondary pumps.

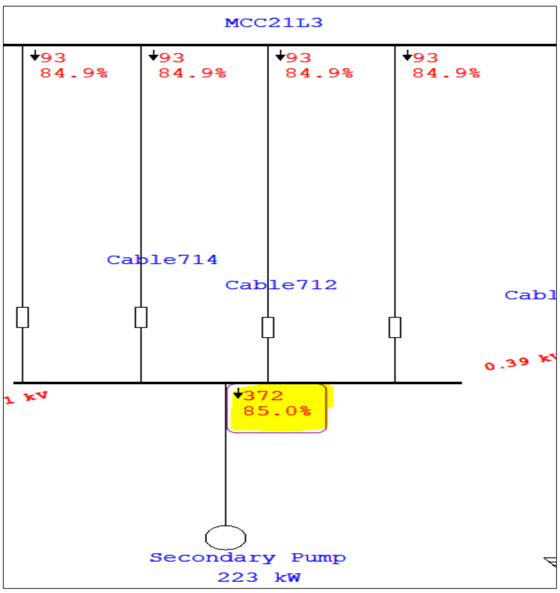


Fig. 4: Load flow simulation results without VFD

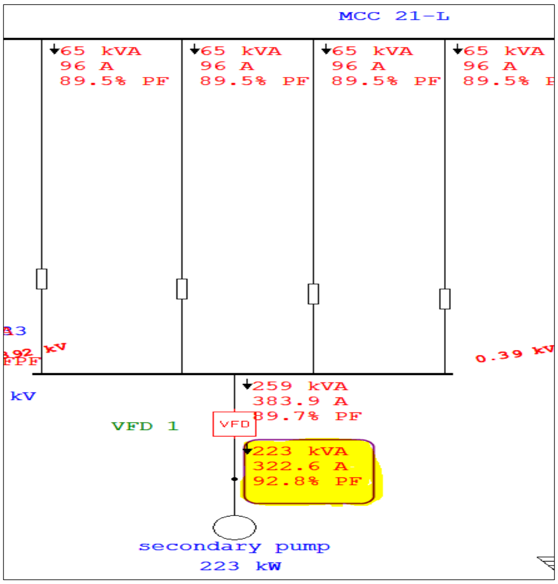


Fig. 5: Load flow simulation results with VFD

Table 9: Total voltage harmonic distortion results

Total voltage harmonic distortion VTHD (%)	Without VFD	With VFD
Bus 533(where VFD installed)	0.72	2.94
Main transformer T1(low voltage)	0.75	2.6

Table 10: Simulation results for calculation energy saving

	simulation results
without VFD	Motor Input Current = 372 A PF = 85% Motor Input Power = 214 kW
with VFD	Motor Input Current = 322.6 A PF = 92.8 % Motor Input Power = 207 kW
Power saving Annual energy saving	7 kW (4 % saving) =kW x 80% hrs per year =7*0.8*24*365 =49056 kwh for one pump =2*49056 kwh =98112 kwh for two pumps
Annual cost saving	=kW x 80% hrs per year*(0.07 $/ kwh) =49056 *0.07= $ 3433.92 for one pump =2*3433.92 = $ 6867.84 for two pumps

5. Simulation the Influence of both LEDs lighting and VFDs controller

In this part, results have been matched for the intent of detecting the effect of nonlinear loads with additional nonlinear energy saving loads on the PQ. The results are mainly divided into two sections which are, when the NRR model are operating with the present condition (without LEDs and VFDs) and when installed LEDs lighting and VFDs controller.

Table 11: Simulation results before and after used LEDs lighting and VFDs

	Load flow results	Harmonic results
without LEDs and VFDs	Active power =868 kw Current = 1419 A P.F = 89.9 %	Voltage at low voltage of T1=0.39kv, VTHD = 0.75 % Current at T1 =51.2 A, ITHD = 1.75 %
With LEDs and VFDs	Active power =800 kw Current = 1403 A P.F = 88 %	Voltage at low voltage of T1=0.39 kv, VTHD = 2.16 % Current at T1 =50.8 A, ITHD = 6.56 %
Economics	Power saving =68 kw (8% saving) Annual energy saving =63072+ 49056 = 112128 kwh Annual cost saving =$4415.0 4+$ 3433.92 =$7848.96	

Table 11 shows the power quality parameters. According to the table, the implementation of LED lighting and VFDs have resulted in a significant reduction of 68 kW which is equivalent to 8% saving of total demand of NRR. Also the model shows that 112128 kwh and the cost of $7848.96can be saved when LEDs lighting and VFDs controller will be used. The influence of huge number of LED lamps and VFDs on the power quality was noticed. The major harmonic distortion was occurred at low voltage side of distribution transformer with VTHD and ITHD up to 2.16%, 6.56% respectively and did not exceed the IEEE standard limits.

6. Conclusion

In this paper, replacement of conventional lighting system with energy saving lighting system is analyzed. Simulations are performed to compare the power quality impact of high permeation of LED lamps instead of IL, FL, HPS lamps and when installed VFDs to control the secondary pumps of NRR. The results show that (1) active power consumed, current and power factor reduce, while

VTHD and ITHD increase clearly. (2) Active power consumed ,current and power factor reduces by 68 kW, 16A, 1 % respectively.(3) total voltage harmonic distortion (VTHD) in the main transformer is almost the triple from 0.75% to 2.16% as a result of used this loads and current total harmonic distortion (ITHD) at the main transformer from 1.75% to 6.56%and 5th, 7th, 11th are the most dominant(4) In view of electricity metering, the amount of 68 kW (8%) can be saved for used additional nonlinear energy saving loads and a total of 112128 kwh can be saved annually which cost $7848.96 (5) According to the recorded results, the increase in energy efficiency is achieved but reduction of power factor and harmonics distortion are significant with additional nonlinear energy saving loads. The issue is urgent with the continuing using energy saving loads and reduction of power factor so must be using compensation system, with respect to power quality problems.

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