Inrush current and Total Harmonic Distortion Transient of Power Transformer with Switching Capacitor Bank

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Abstract**—** Transient causing overvoltages occur in the system due to different causes, and the peak values of these can be much in excess of the operating voltage. Therefore, an area of critical importance in the design of power systems is the consideration of the insulation requirements for lines, cables and stations. Transient overvoltages due to the energizing of capacitor banks are the most common source of overvoltages on many power systems. There is however a problem that is associated with the switching of a capacitor bank. Transient overvoltages are always created during this switching. **This paper** analyzes the instantaneous values of the voltages during the capacitor banks switching. Several switching cases are developed represented and simulated using MATLAB/SIMULINK software in order to evaluate the conditions which affect the associated capacitor bank energization transient overvoltage. The simulations tacked into account the operation of different switches, **using the Fast Fourier Transfer (FFT) the total harmonic content of transient overvoltages and currents waveforms is estimated at all system buses.**

Keywords-component; Switching capacitor bank; Transient overvoltages and currents; Fast Fourier Transfer (FFT)

I. INTRODUCTION

Modern civilization makes use of large amounts of energy to generate goods and services. From the industrial plants, providers of public services to the ordinary man, all of them need energy to satisfy and create the wellbeing of modern society. Switching of capacitor banks and shunt reactors usually occurs quite frequently even in a daily basis, since their connection to the network is essential due to reactive compensation reasons, improving thus the power quality at least locally. However, their energization has been recognized as a possible source of malfunctions for many years [1]. The purpose of electric power systems is to provide energy for human use in a secure, reliable and economic manner. Electric power systems are made up of facilities and equipments that generate, transmit and distribute electrical energy.

The components in a substation are mostly inductive in nature and with the addition of capacitor banks, the system losses are reduced by improving the power factor of the system. These capacitor banks are normally switched on during peak loading periods and switched off during light loading periods. Such connecting of a capacitor bank to the bus line results in a rise in the voltage level of the system [2]. The interruption of a capacitive current can cause dielectric problems for the switching device, but when a capacitor bank is taken into service, large inrush currents can flow through the substation and can cause problems for the protection system [3]. These types of disturbances in power systems may cause persisting mal-function in protection systems and may reduce the power transformer life time and consequently, may damage the plant and causing of power discontinuity of the electrical energy [4]. When the capacitor bank switching device is closed to energize the capacitor bank, the voltage of the switched capacitor bank bus suddenly collapses to the level of the voltage on the capacitor bank which the capacitors discharged is generally zero. The bus voltage then attempts to return to its normal power frequency value, but overshoots this value and oscillates about the normal power frequency wave until the oscillations are damped [5,6].

The system studied has two main lines, 30 km and 90 Km long, transmit power from a generation plant (2 generators) to an equivalent network having a load circuit, the system has been investigated for its switching overvoltages, performance inrush current in transformers caused by switching normal operating on/off and switching of capacitor bank (power factor correction).

The main objective of this paper is investigating the inrush current and analyzing the different effects of the bank capacitors switching in substation for the purpose of power factor improving correction. Two different power systems are simulated to demonstrate the different effects of switching power factor correction. Many program scripts are developed for the purpose of analyzing the overvoltage waveforms which are analyzed using the fast Fourier transfer FFT. All components in a utility are made of capacitive and inductive parameters. In an alternating current circuit, energy is transferred cyclically between the inductances and the capacitances of the circuit as the current and voltage rise and fall at the frequency of the supply [7].

The overvoltages appear on the local and remote capacitor connected buses in the power systems are discussed to determine the Total Harmonic distortion (THD) using the Fast Fourier Transfer (FFT), content of voltage and current waveforms at all buses. This investigation is modeled using MATLAB / SIMULINK software package.

II. SYSTEM MODELING AND METHODOLOGIES

A. Power system configurations

The electrical power system under study is three-phase system of 69/13.8 kV power system distribution electrical power between two power plants as presented in Fig. 1. Different transmission lines parameters, Substations transformers parameters are illustrated in Table I and Table II.

The system has two main lines, 30 km and 90 Km long, transmit power from a generation plant (2 generators) to an equivalent network having a load circuit is showing in Table III connected to the power systems under study. The system has been investigated for its switching overvoltages, performance overvoltage at transformers caused by switching operating on/off and switching of capacitor bank (power factor correction).The overvoltages appear on the local and remote capacitor connected buses in the power systems are discussed to determine the Total Harmonic distortion (THD) using the Fast Fourier Transfer (FFT), content of voltage and current waveforms at all buses.

Different cases of study are demonstrated the switching capacitor bank at different locations in the system. The switching operation of all cases is one switching capacitor per case. The condition will be more severe in the case of switching on the different amount of capacitor bank at loading condition. The effects and determination of the relative locations of the switched capacitor bank as following cases:

TABLE I: The transmission line parameters

Line No.	R1 (Ω/km)	R_o (Ω/km)	L (mH/km)	L_o (mH/km)	C ($_P$F/km)	C_o ($_P$F/km)
$T.L_1$	0.00265	0.0795	16.3	1.18	0.00265	0.0795
$T.L_2$	0.00232	0.0696	13.4	0.97	0.00232	0.0696
$T.L_3$	0.00208	0.084	4.9	0.358	0.00208	0.084
$T.L_4$	0.00299	0.0879	7.1	0.518	0.00299	0.0879
$T.L_5$	0.00143	0.0429	3.4	0.2482	0.00143	0.0429

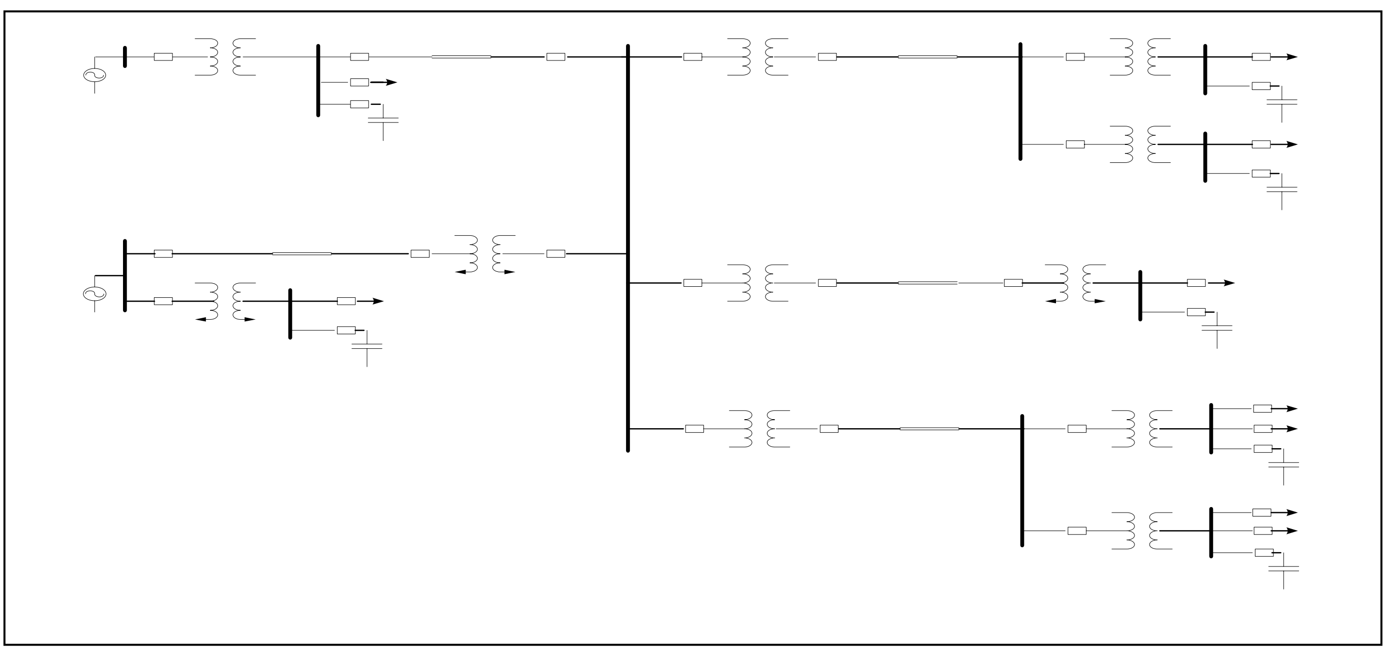


Figure 1: Single line diagram for 69/13.8 kV electrical power system under study.

TABLE I: The different transformers parameters

Trans. No.	MVA	kV	R1 (Ohm)	L1 (H)	R2 (Ohm)	L2 (Ohm)
T1	200	230/69	3.52	1.59	0.0092	0.3403
T2	50	69/13.8	0.46	0.0012515	0.0183	0.00054557
T3	3.75	13.8/4.16	0.49	1.347E-04	0.0147	0.00010662
T4	1.5	13.8/4.6	1.22	3.367E-05	0.00147	0.0003255
T5	30.5	13.8/0.48	0.061	0.0419	7.20E-05	8.415E-09
T6	30.25	13.8/0.48	0.061	0.0026051	7.30E-05	8.687E-09
T7	30.725	13.8/2.4	0.059	0.0018743	5.40E-03	1.541E-05
T8	3.5	13.8/0.48	1.22	0.0000079	1.40E-03	1.77E-06
T9	200	13.8/69	0.233	0.0001455	0.46	0.001251
T10	50	69/13.8	0.46	0.001251	0.0183	54.56E-05
T11	100	69/13.8	0.46	0.001251	0.0183	54.56E-05

TABLE III: The different load parameters

Load No.	KV	P(MW)	Q(MVAR)	
			Qxl	Qxc
1	69	2.1	2.36	0.236
2	0.48	1.05	1.178	0.1178
3	4.16	1.2075	1.355	0.1355
4	4.6	0.875	0.982	0.0982
5	0.48	1.05	1.1783	0.11783
6	0.48	0.7	0.7855	0.07855
7	0.48	0.35	0.3927	0.03927
8	2.4	1.4	1.5711	0.15711
9	2.4	1.225	1.375	0.13745

B. Fourier transform and the FFT in MATLAB

Block-cyclic distribution is more efficient because it induces load-balancing, or splitting the work evenly between processors during most computations. This property is important because by splitting the work evenly among the processors, it allows for a greater degree of speed-up as no one processor will be dragged down by a disproportionate amount of work. In addition, block-cyclic distribution is more effective because of its scalability and reduction in communication properties.

By considering the question of, trying to detect an underlying sinusoidal signal component that is buried in noise. Such problems occur, FFT function in (PowerGUI) Matlab Simulink toolbox is an effective and powerfull toolbox for computing the discrete Fourier transform of a signal and GUI. The FFT in Matlab is used to calculate the discrete Fourier transform. MATLAB uses the Fourier transform convention equivalent to the continuous integral transform the discrete version of the Fourier transform, the FFT and its inverse, used by MATLAB is the same as the standard FFT algorithm in Numerical Recipes. MATLAB's FFT calculates the equivalent of the discrete sum:

$$F_K = \sum_{n=1}^{N} f_n e^{-i2\pi(K-1)(n-1)/N} \qquad ,1 \le K \le N \tag{1}$$

With F_k the discrete Fourier transform of any discrete signal (with index n = 1, 2, ... ,N)

The DFT of a vector *x* of length *n* is another vector *y* of length *n*:

$$y_{p+1} = \sum_{j=0}^{n-1} \omega^{jp} x_{j+1} \tag{2}$$

The first element of y, corresponding to zero frequency, is the sum of the data in *x*. This DC component is often removed from *y* so that it does not obscure the positive frequency content of the data [8]. The voltage and current harmonics during the switching are performed by used Fast Fourier Transfer (FFT) for the different switching bank at each bus. The different scenarios (cases) for switching the different capacitors are monitored with their effects of overvoltages and overcurrents regarding their peak values and total harmonic distortion and the numbers of the cycles.

Translating between block-cyclic data distribution and a row or slab data distribution seems like a simple task: determine the sending and receiving processor and then issue the communication between the two processors. Unfortunately, because both the sending and receiving processor must know its destination and source respectively, this task becomes an onerous one because each and every single processor must have some method of determining whether or not it should receive or send or do neither to any position in the distributed matrix.

III. SIMULATION RESULTS

The Total Harmonic Distortion (THD) effects of the capacitor bank at each bus of the power system utility under study are analyzed using FFT toolbox. The system configuration shown in Fig. 1 is analyzed for inrush currents along the 69/13.8 kV and distribution power system. Statistical cases involving one switching capacitor bank simulation on/off per case were performed to obtain the THD at each bus. The condition will be more severe in the case of switching on the different amount of capacitor bank at loading condition. Moreover, it was assumed that shunt capacitors at other transformers terminals (bus-bars) are switched-off during line energization and reclosing. Furthermore, only one capacitor bank is switching on/off per case. The shunt capacitor banks are located at bus-bars B2, B4, B5, B7 and B9 to achieve the power factor at those bus-bars to 90 %, the different capacitor values are presented in Table IV. The actual power factor and the MVAR are calculated at each bus during the normal loading conditions. The capacitors bank values are calculated at each bus to improve the power factor from its actual value to be 0.9.

TABLE IV: The different values of the capacitor banks at each bus.

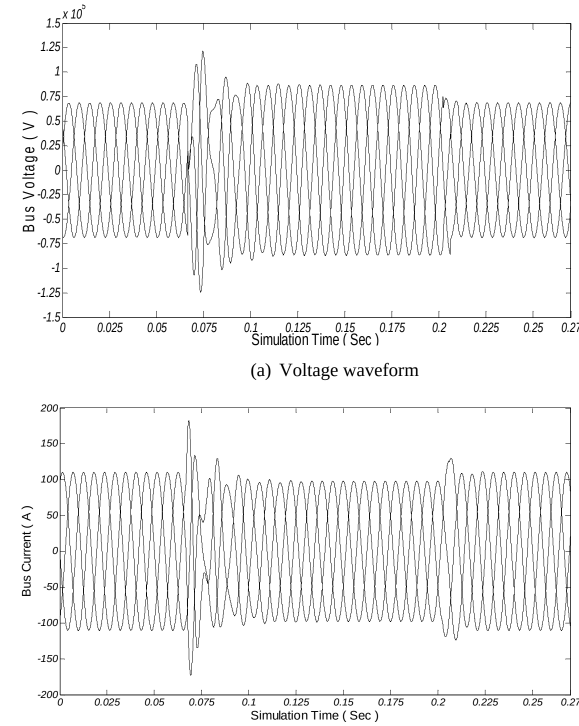
Capacitor No	Cap.1	Cap. 2	Cap.3	Cap.4	Cap.5	Cap.6	Cap.7
M VAR	9.2	1	1.045	0.75	0.87	0.9	2.3

IV. ANALYSING THE RESULTS

Several conditions required by the industry are considered for the utility capacitor bank energization. Which are showing in Figs. (3c, 4c, 5c, 6c) it is assumed that, the power factor is corrected from values 0.64 to 0.90.

Several cases are simulated using MATLAB/SIMULINK software, in order to evaluate the conditions which affect the associated capacitor bank energization transient intensity. The cases in which the capacitor banks are energized during transformers current is used as reference for several simulations where one capacitor bank operation in every case.

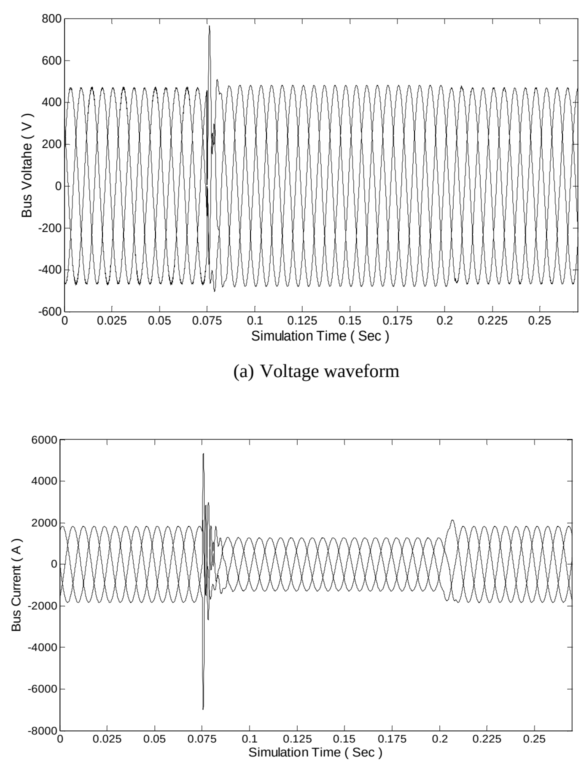
In Table VI some of the obtained maximum overvoltage values of transmission system are presented at bus B5 in first case. The table shows the peak voltages values at different locations of the transmission system for the switching of the capacitor banks. Figs. (2, 3, 4, 5 and 6) show the Three-phase voltage and current waveforms at switching buses (B2, B4, B5, B7 and B9) respectively, amplification of the transient overvoltage at these bases is experienced. Transient overvoltages produced via the energy exchanges between the various inductances and capacitances of the network. the maximum overvoltage occurring in the modeled system at bus B5 (4.16 KV) reached to the value 1.817 p.u as illustrate in Table VI, the worst case in this system occur during switching-on the capacitor bank at this bus (B2).



(a) Voltage waveform

(b) Current waveform

Figure 2: The developed model's voltage and current waveform for switching case1 at bus B2



(a) Voltage waveform

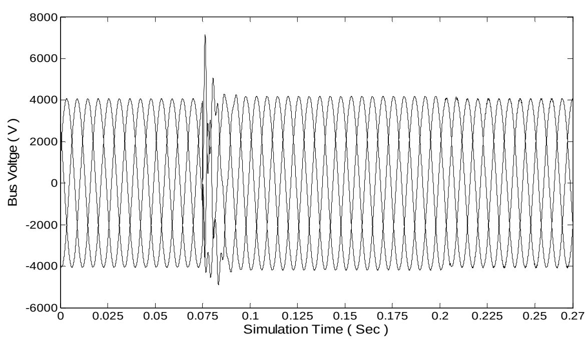
(b) Current waveform

Figure 3: The developed model's voltage and current waveform results for switching case 3at bus B4

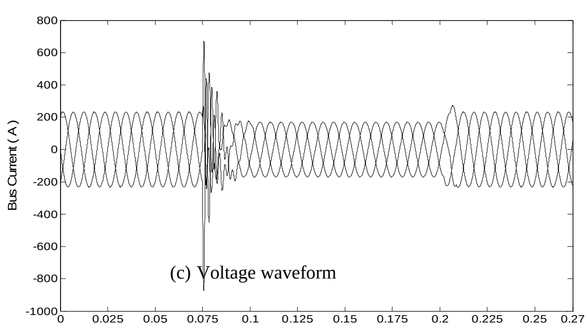
Therefore, it is effect of overvoltage at all bases. Table VI illustrate the overvoltage and Total Harmonic Distortion (THD) at every switching capacitor bank cases, and Table VI illustrate the overvoltage and Total Harmonic Distortion (THD) at every switching capacitor bank cases. It is clear that the maximum THD and overvoltage occur at case1, also can be not that the maximum overvoltage occur at switching bus in all cases.

A. Transient Currents

High current values can appear in the system due to capacitor bank switching and they can last various cycles. For the power factor correction capacitors with load current in all cases were inrush currents at switching buses as shown in Figs. (2b, 3b, 4b, 5b and 6b). the maximum inrush current in per unit occur at bus B4 As show in Table V and the maximum of Total Harmonic Distortion of current appear at bus B5, Where have larger capacitor bunk size, and load. The maximum inrush current at this case was 3.8 p.u. In Fig. 4, the current which appear at the switching capacitor bank (Cap.2) is presented high frequency component can be observed for various cycles.

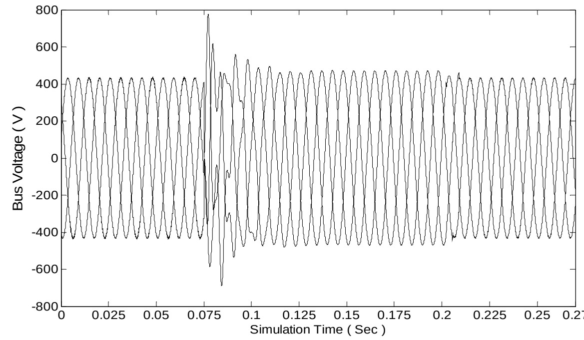


(b) Voltage waveform

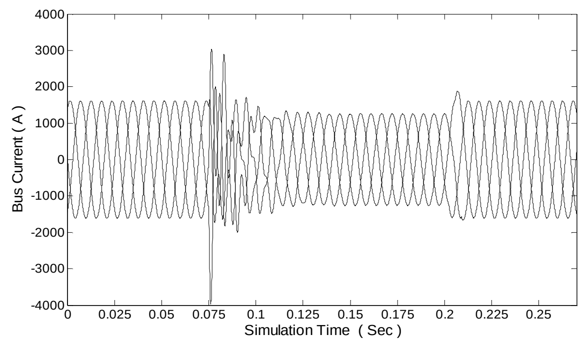


(c) Current waveform

Figure 4: The developed model's voltage and current waveform results for switching case 3 at bus B5.

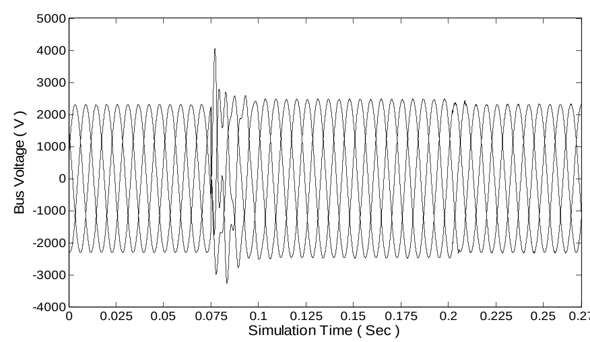


(d) Voltage waveform

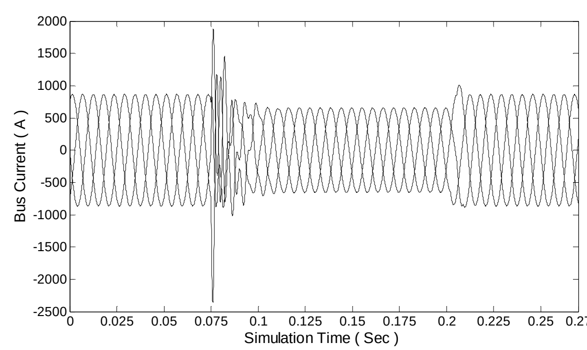


(b) Current waveform

Figure 5: The developed model's voltage and current waveform develop results for switching case 4 at bus B7.



(e) Voltage waveform



(d) Current waveform

Figure 6: The developed model's voltage and current waveform results for switching case 3 at bus B5.

B. Current Harmonic component

The current harmonics distortion during the capacitor bank switching by using Fast Fourier Transform (FFT) was performed [9.10]. In Figs. (7a, b, 8a, b, 9a, b, 10a, b and 11a, b) the main current harmonic components for the switching in all cases can be observed. Fig. (9a) shows the maximum current harmonic components for the switching capacitor bank in case 3 developed at switching bus B5. It should be noted that the current, harmonics are predominantly in the range of 2063 Hz

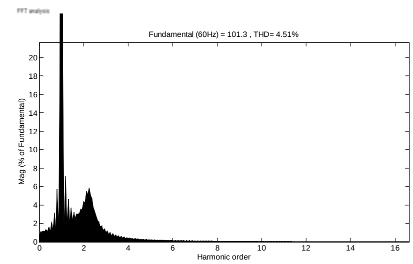
It should be noted that , in the case of the current voltage 60 Hz component mainly appears, the harmonics are predominantly in the range of 101.3-2063 Hz.

V. CONCLUSION

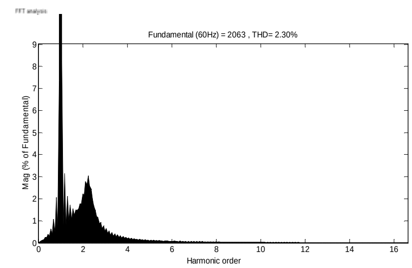
In this paper characteristics of transients, which originated from utility capacitor bank switching, are studied. Factors that influence the intensity of such transients current are investigated in order to identify the conditions in which these effects can be undermined. The effects of bus voltages due to switching on/off of the power capacitors are investigated. And the Total Harmonic Distortion (THD) is calculated for current.

From the study results, the following main conclusions could be drawn:

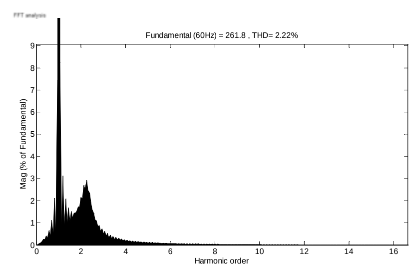
1. The inrush current effect of power capacitor switching on is limited for improving the power factor to its local bus more than the remote buses.
2. Severe harmonic and inrush currents could appear during capacitor bank energization is depending on capacitor bank size and load.



Current (THD) at switching bus B2 phase (3) = 4.51 %

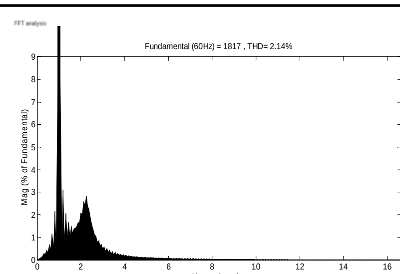


Current (THD) at bus B4 phase (3) = 2.3 %

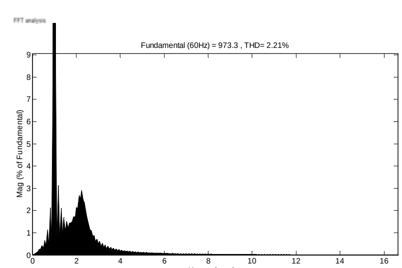


Current (THD) at bus B5 phase (3) = 2.22 %

Figure7a: Total Harmonic Distortion (THD) the developed model's results switching case 1(at bus B2) and buses B4,B5

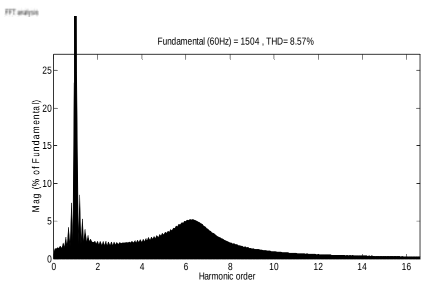


Current (THD) at bus B7 phase (3) = 2.14 %

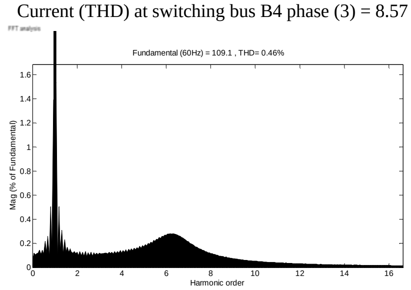


Current (THD) at bus B9 phase (3) = 2.21 %

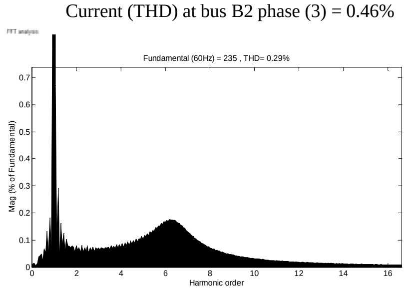
Figure7b: Total Harmonic Distortion (THD) the developed model's results switching case 1at buses B7, B9.



Current (THD) at switching bus B4 phase (3) = 8.57 %

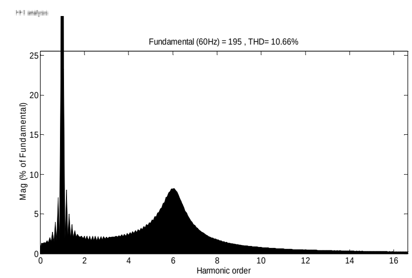


Current (THD) at bus B2 phase (3) = 0.46%

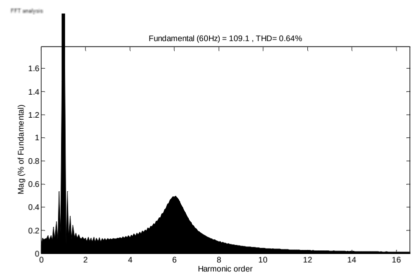


Current (THD) at bus B5 phase (3) = 0.29%

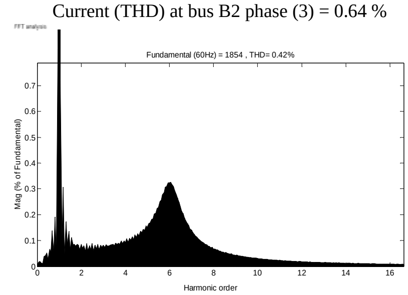
Figure 8a: Total Harmonic Distortion (THD) the developed model's results switching case 2(at bus B4) and buses B2,B5



Current (THD) at switching bus5 phase (3) = 10.66 %

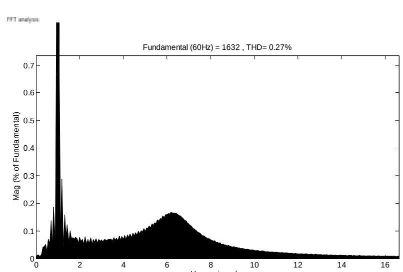


Current (THD) at bus B2 phase (3) = 0.64 %

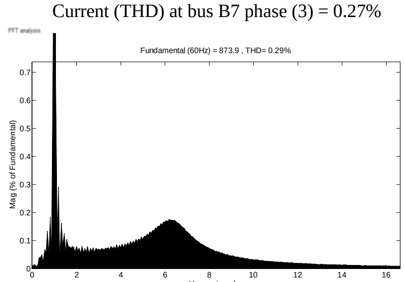


Current (THD) at bus B4 phase (3) = 0.42%

Figure 9a: Total Harmonic Distortion (THD) the developed model's results switching case 2(at bus B4) and buses B2,B5

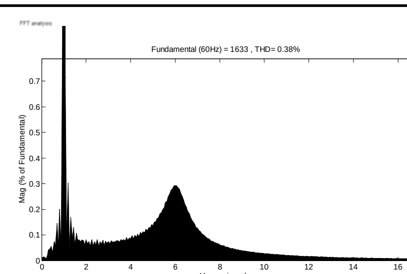


Current (THD) at bus B7 phase (3) = 0.27%

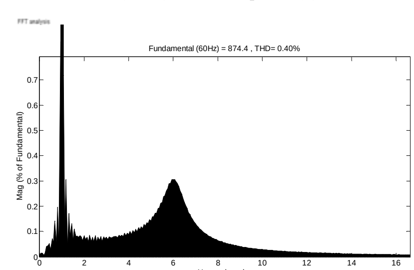


Current (THD) at bus B9 phase (3) = 0.29%

Figure 8b: Total Harmonic Distortion (THD) the developed model's results switching case 2at buses B7,B9.

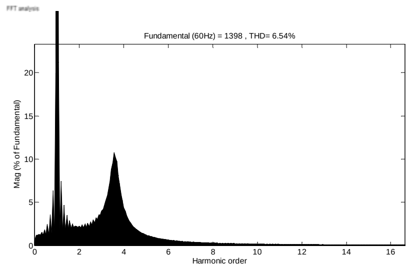


Current (THD) at bus B7 phase (3) = 0.38%

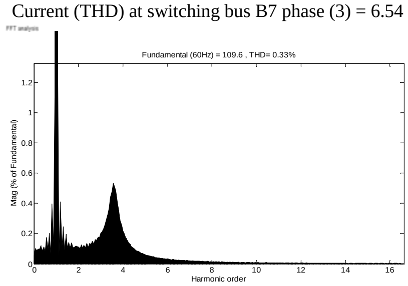


Current (THD) at bus B9 phase (3) = 0.40%

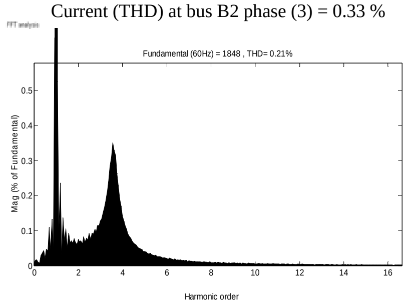
Figure 9b: Total Harmonic Distortion (THD) the developed model's results switching case 3at buses B7, B9.



Current (THD) at switching bus B7 phase (3) = 6.54 %

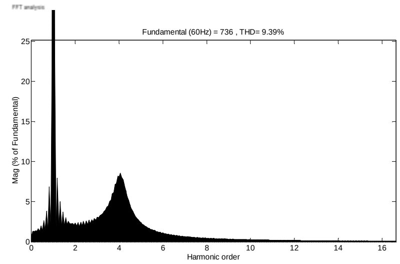


Current (THD) at bus B2 phase (3) = 0.33 %

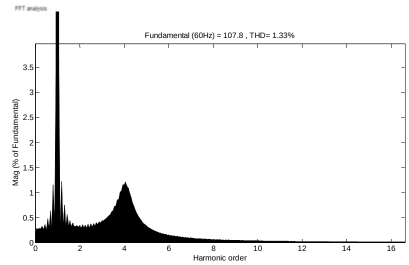


Current (THD) at bus B4 phase (3) = 0.21%

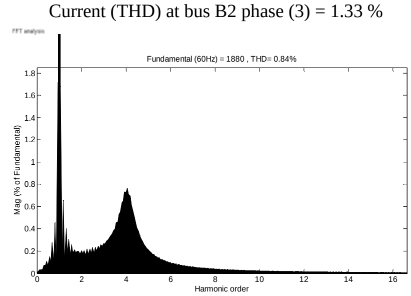
Figure10a: Total Harmonic Distortion (THD) the developed model's results switching case 4 (at bus B7) and buses B2,B4



Current (THD) at switching bus B9 phase (3) = 9.39 %

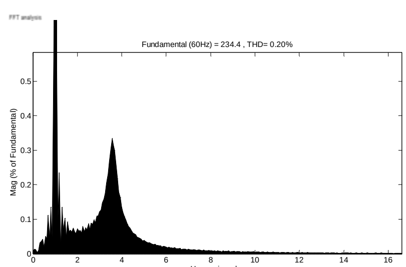


Current (THD) at bus B2 phase (3) = 1.33 %

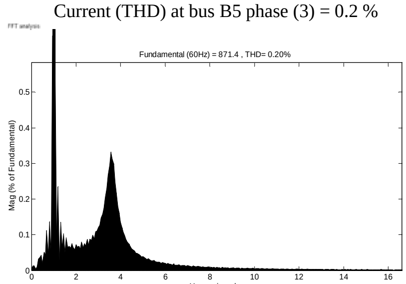


Current (THD) at bus B4 phase (3) = 0.84%

Figure 11a: Total Harmonic Distortion (THD) the developed model's results switching case 5 (at bus B9) and buses B2,B4

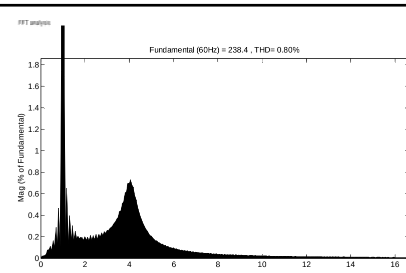


Current (THD) at bus B5 phase (3) = 0.2 %

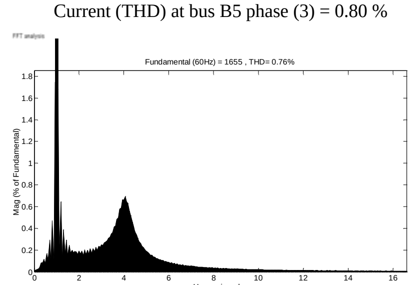


Current (THD) at bus B9 phase (3) = 0.2 %

Figure 10b: Total Harmonic Distortion (THD) the developed model's results switching case 4 at buses B5,B9.



Current (THD) at bus B5 phase (3) = 0.80 %



Current (THD) at bus B7 phase (3) = 0.80 %

Figure 11b: Total Harmonic Distortion (THD) the developed model's results switching case 5 at buses B5,B7.

TABLE VI: The Inrush current and Total Harmonic Distortion (THD), Based on the measurement analysis of current waveform by calculated using Fast Fourier Transfer (FFT) at every bus.

Bus switching	B2			B4			B5			B7			B9		
	O.V	THD	NO.of cycle	O.V	THD	NO.of cycle	O.V	THD	NO.of cycle	O.V	THD	NO.of cycle	O.V	THD	NO.of cycle
B2	1.815	4.09	1.25	1.8	4.11	0.75	1.817	4.09	0.75	1.795	3.94	0.75	1.81	4.07	0.75
B4	1.532	1.5	0.25	1.622	1.84	0.25	1.535	1.5	0.25	1.515	1.42	0.25	1.53	1.49	0.25
B5	1.578	1.96	0.5	1.57	1.98	0.5	1.77	2.55	0.5	1.561	1.86	0.5	1.577	1.95	0.5
B7	1.1	0.58	0.125	1.09	0.59	0.125	1.01	0.58	0.1	1.795	3.07	1.5	1.1	0.58	1
B9	1.515	2.63	0.75	1.505	2.65	0.75	1.502	2.63	0.75	1.514	2.51	0.75	1.748	3.53	0.75

TABLE V: The Overcurrent and Total Harmonic Distortion (THD), Based on the measurement analysis of current waveform calculated using Fast Fourier Transfer (FFT) at every bus.

Buses	B2			B4			B5			B7			B9		
	Inrush current	THD	NO.of cycle	Inrush current	THD	NO.of cycle	Inrush current	THD	NO.of cycle	Inrush current	THD	NO.of cycle	Inrush current	THD	NO.of cycle
B2	1.64	4.51	2	1.53	2.3	1.75	1.15	2.22	2.5	1.575	2.14	2	1.53	22.1	1.25
B4	1.15	0.46	1	3.8	8.57	1.25	1.06	0.29	1	1.15	0.27	1	1.09	0.29	0.25
B5	1.17	0.64	2	1.2	0.42	1.25	3.6	10.66	1.25	1.17	0.34	0.75	1.11	0.4	0.25
B7	1.08	0.33	0.75	1.04	0.21	1	1.01	0.2	1	2.57	6.54	2.25	1.1.04	0.2	1
B9	1.28	1.33	0.25	1.12	0.84	0.25	1.08	0.8	0.25	1.15	0.76	0.25	2.72	0.76	2

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