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Harmonic Analysis of Power Systems in Order to Network Conversion

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Abstract – *Conversion of 3-phase single-circuit (3PSC) to 3-phase double-circuit (3PDC) and 6-phase single-circuit (6PSC) transmission line is a well known method to increase the power transfer capability of the network. The constraints using to decide on conversion type are usually network total loss and desirable voltage limits; while the harmonic effects are omitted. However, harmonics lead to undesirable power quality and increase total loss of the network. Thereby, in order to obtain the accurate result to adopt an optimal scheme for network conversion, harmonics should also be considered. In this paper a harmonic analysis due to the conversion of 3PSC to 3PDC and 6PSC network is performed. The analysis is applied to a real study system by conversion of the entire and just one of the existing lines of the network, separately. The results show that, when harmonic effects are considered or omitted, the criteria needed to make a decision on the options existed for network conversion could change. Due to the obtained results, telephone influence factor (TIF) of currents and total harmonic distortion (THD) of voltages are dependent on conversion type together with the harmonic sources of the network. However, in 6PSC conversion compared to 3PDC conversion type, the number of resonances is increased and propagation of high frequency disturbances is decreased.*

***Keywords**: Harmonic Analysis, Network Conversion, Current TIF, Voltage THD*

Nomenclature

h	Harmonic order
R	Resistance
X	Reactance
Z	Impedance
Y	Admittance
V	RMS voltage
I	RMS current
S	Apparent power
Q	Reactive power
P	Active power
D	Conductor diameter
F	Electric signal
W	Weighting factor
Subscripts	
h	Harmonic order
l	Leakage
f	Frequency
0	Zero sequence
+	Positive sequence

I. Introduction

Traditionally, the need for increasing the power transfer capability and more efficient use of ROW space has been accomplished by the use of successively higher system voltages.

Constrains on the availability of land and planning permission for overhead transmission lines have renewed interest in techniques to increase the power carrying capacity of the existing ROWs. HPO transmission was conceived as a means for increasing the power transfer capability of the existing ROW space [1].

Among the HPO, six-phase transmission appears to be the most promising solution to the need to increase the capability of existing transmission lines and responds to the concerns related to electromagnetic fields [2]. Three-phase line can be converted to a six-phase line using conversion transformers, which make the required 60° phase shift at six-phase side [3].

Some other advantages of 6PSC transmission over the conventional 3PDC system are: smaller structure, improved voltage regulation [3], lower corona and field effects, and more stability margin [4].

In [5], results illustrate that the use of 6PSC transmission fitted with compact structures can be a cost effective solution. In other words, the cost penalty for constructing a 6PSC line versus a 3PDC line with the same voltage level is not excessive, particularly if physical constraints exist. The high cost of terminals, due to application of phase conversion transformers, is compensated by reduced compact structures, foundation cost, ROW cost and probably losses percentage [3].

Also, nowadays the conversion of 3PSC to the conventional 3PDC transmission lines is a method to

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increase the transfer capability of the network. The concern about 3PDC or 6PSC conversion is that the effect of harmonics is not considered to decide on the conversion type; while in order to get the accurate results, such effects should also be considered.

Power quality problems have negative effects on the energy system components. These problems such as voltage harmonics and especially current harmonics can severely impact the loads in electrical systems [6]. Harmonic analysis is a very important subject in power systems and one of the well known aspects of power quality monitoring and control. Ever-increasing use of nonlinear loads, power electronic devices and equipment in power systems, make the harmonic distortion more and more serious [7]-[8]. Beside, harmonic currents generated in one area can penetrate into the power grid and propagate into other areas, resulting in voltage and current distortions for the entire system. The presence of harmonics can give rise to a variety of problems including equipment overheating, deteriorated performance of electrical equipment, the incorrect operation of protective relays, interference with communication devices, apparatus dielectric failure and so on [9]-[10]. Hence, IEEE Std. 519 [11] recommends practices for utilities and customers to limit the harmonic contents in power systems. Thereby, harmonic analysis, as a significant factor for power system optimization, should also be considered.

In this paper, in addition to conventional parameters, i.e. power system loss and voltage profile, harmonics are investigated in order to obtain the harmonic criteria needed to make a decision on the best option existed for network conversion. In order to go through this, two analytical methods consisting of harmonic load flow and harmonic frequency scan are executed. To make a comparison, the results are determined with and without considering system harmonics. In this work, conversion of the entire network and just one of the existing 3PSC lines to 3PDC and 6PSC line have been investigated, separately.

II. Harmonic Analysis

II.1. Modeling of the Harmonic-Producing Devices

For harmonic analysis, frequency characteristics and the non-linearity of power system devices must appropriately be recognized and modeled. Depending on their nature and behavior, these devices are modeled in very different ways. A detailed summary on this topic can be found in [12].

In general, non-linear loads in power systems are essentially either injecting the harmonic currents into the system being modeled by harmonic current source or applying the harmonic voltages at the given points being modeled by harmonic voltage source. Non-linear loads that could be modeled as a harmonic current source are: static loads, UPSs, chargers/converters, VFDs and saturated transformers (especially when they are lightly loaded). However, chargers/converters, and static loads can also be modeled as harmonic voltage sources, if they primarily cause voltage distortion instead of current distortion. But, in view of the fact that these devices often cause more current distortion than former, they are often modeled as the harmonic current sources.

Also, usually inverters, “harmonic polluted” power grids (utilities) and saturated synchronous generators can be modeled as harmonic voltage sources if they contain significant voltage distortion.

II.2. Modeling of the Non Harmonic-Producing Devices

This subsection summarizes the typical representations of common network components for harmonic analysis. The detailed representations could be seen in [13].

Overhead lines: Typical overhead lines can be modeled as a multiphase coupled equivalent pi-circuit. For balanced harmonic analysis, the model can be further simplified into a single-phase pi-circuit determined from the positive sequence impedance data of the line. The main concerns for modeling the overhead lines are:

a) The frequency-dependency of the series impedance, and;

b) The distributed-parameter nature (long-line effects) of the series impedance and shunt capacitance.

Transformers: To determine the harmonic impedance of the transformers, they are modeled by series combined of resistance and inductive reactance as below:

$$Z_h = R \times \sqrt{h} + jX_l \times h \tag{1}$$

A frequency-dependent coefficient can be considered to include the skin effects for each of the impedances. Also, the magnetizing admittance is usually ignored since under normal operating conditions its contribution is not significant [13].

Rotating machines: In a synchronous or induction machine, the rotating magnetic field created by stator harmonics rotates at a speed significantly higher than that of the rotor. Therefore, at harmonic frequencies, the impedance approaches the negative sequence impedance. In each case the frequency-dependency of the resistance can be significant due to skin effects and eddy current losses.

Passive loads: The harmonic impedance of a linear passive load is calculated from its fundamental loading using an equivalent parallel *R* and *X* circuit. Considering skin effect, the reactance and resistance of its harmonic impedance are respectively adjusted linearly and non-linearly based on the order of considered harmonic.

Note: It is necessary to point out that for the triple harmonics (3rd, 9th, …) existing in the system, the zero sequence impedance of all components is used with the adjustment to desirable harmonic frequency. Moreover, type of winding connections, grounding methods and impedances will affect on the flow of triple *n*th harmonic in the system.

II.3. Harmonic Indices

In general, the harmonic voltage is the most significant issue of power quality caused by harmonic distortions; while the harmonic current effectively interfere with the adjacent communication systems [10]. In harmonic analysis, there are some indices used to describe the effects of harmonics [11], [14]. The most common indices, which are also used in this paper, are described as below:

1) *RMS* value of a waveform is calculated as follows:

$$RMS = \sqrt{\sum_{h=1}^{\infty} F_h^2} \tag{2}$$

2) *THD* that is a measure of how much harmonic content there is in a waveform. *THD* is defined by the equation [15]:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \tag{3}$$

3) *TIF* that is a measure used to describe the interference of a power transmission line on a telephone line. It is a variation of *THD* with a different weight given to each of the harmonics based on its amount of interference to an audio signal in the same frequency range. *TIF* index is determined by:

$$TIF = \frac{\sqrt{\sum_{h=1}^{\infty} \left(W_h V_h\right)^2}}{\sqrt{\sum_{h=1}^{\infty} V_h^2}} \tag{4}$$

The values of the weighting factors for different harmonic frequencies are given in IEEE Std. 519 [11].

II.4. Harmonic Frequency Scan

One particular concern with harmonics is the resonance condition in power system. In general, there are only two resonance types which are probable to be occurred in any power system. The points of change from inductive to capacitive mode of the impedance characteristic of a power system, is called parallel resonance. On the contrary, it is called series at the changing point of capacitive to inductive mode. Further, in parallel resonance phenomenon the impedance increases exponentially until it reaches the maximum and then in the same manner decreases with the frequency. Conversely, the impedance decreases exponentially until it reaches the lowest magnitude then increases steadily with the rise of frequency in the series phenomenon. If the resonance occurs at a bus where a harmonic source is connected to the system, an overvoltage (in parallel resonance) or overcurrent (in series resonance) condition will be observed.

Usually, frequency scan is the first step in a harmonic study and is the most effective tool to detect the resonance condition in a power system; as any resonance condition and relevant triggering frequency can be clearly identified by frequency scan [16].

Typically in the frequency scan, 1 p.u. sinusoidal current is injected into the bus of interest and the voltage is calculated. The bus of interest is where a harmonic source exists. This calculation is repeated using discrete frequency steps throughout the range of interest. Mathematically, the following equation at frequency *f* is solved:

$$\left[V_f\right] = \left[Y_f\right]^{-1}\left[I_f\right] \tag{5}$$

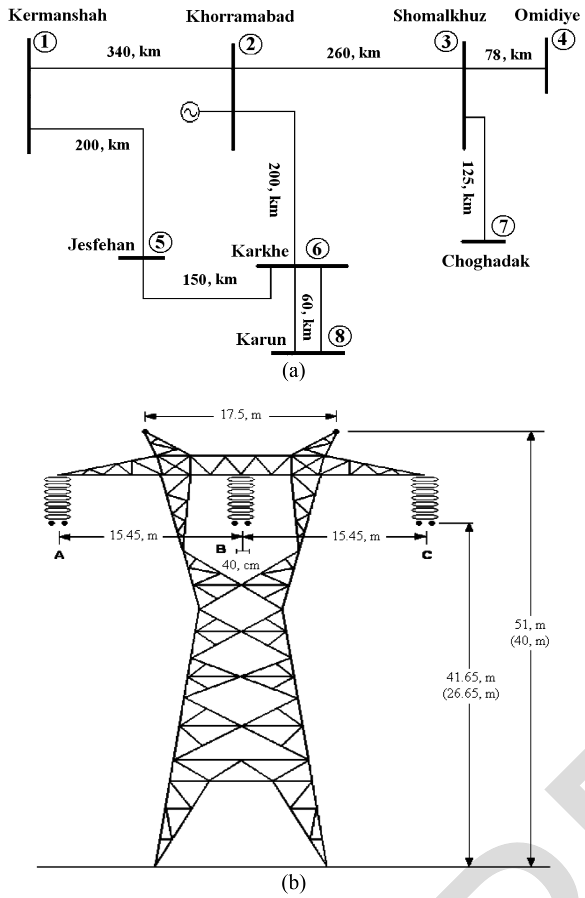
II.5. Harmonic Load Flow Analysis

If one needs to find the harmonic distortion levels for certain operating condition, a harmonic power flow analysis should be executed. Firstly, the harmonic load flow carries out a load flow calculation at the fundamental frequency. Then, the obtained results set the initial values for the voltage and currents that are used to calculate different harmonic indices. For each harmonic frequency, at where the harmonic source exists, a direct load flow is accomplished by means of current injection method. Once the harmonic load flow is executed, harmonic components of the buses voltages and the current of lines are determined and the harmonic indices are obtained. The harmonic frequencies used in this paper to calculate the harmonic indices, are low order frequencies in the range of 2nd to the 15th harmonic order and the characteristic harmonics from 17th up to 73rd harmonic order.

III. The Study System

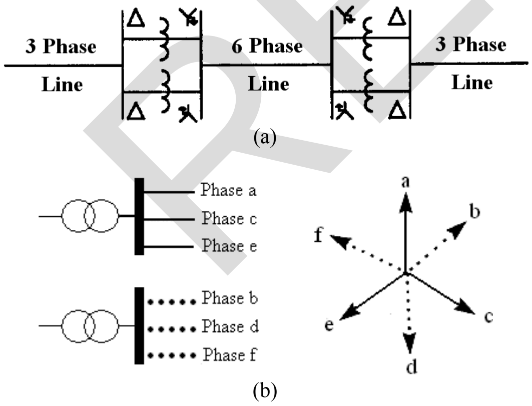
The schematic diagram of the study system is shown in Figs. 1. The selected system is a part of 400 kV Iranian southeast local grid consisting of one synchronous generator, 8 load buses and 9 transmission lines that all are 3PSC. Detailed data of the study system are given in Appendix A. It is assumed that the feeding network behind the buses is in normal ac steady-state condition. The back impedance in each station is modeled by a Thevenin equivalent network, of which the parameters are presented in Table I. There are some common connections and combinations that can be used to form a 3PSC to 6PSC conversion transformer [3]. In this study, candidate lines are converted using Δ-Y and Δ-Inverted Y connected transformers, as shown in Figs.

2. One of each pair of transformers has reverse polarity in order to obtain the required 60° phase shift.



	Type	D, cm	R_+ @ 25°C, Ω/km
Phase conductors	Cardinal	3.04	0.061
Shield wires	7 no. 8 AW	0.98	1.516

Figs. 1. Study system (a) System configuration of local grid, (b) Typical line configuration (values in brackets are mid-span heights)



Figs. 2. Conversion of a 3PSC transmission line to 6PSC line (a) Transformer connections, (b) Phasor diagram

In order to perform harmonic analysis, the following assumptions are also considered:

1- All the loads existed in the power system are composed of two dynamic and static parts. As the dynamic part will not contribute on harmonic producing, only the static part was considered as the harmonic-producing source in simulations.
2- The loads connected at bus#1 and bus#4 are the only harmonic sources existed in the network. The load connected at bus#1, is considered to be a PWM ASD or an EAF load. However, in all studies a 6-pulse rectifier load was also connected at bus#4. The waveform and harmonic spectrum of these loads are shown in Appendix B.
3- The generator, transformers, transmission lines and other loads (except those existed in bus#1 and bus#4) are assumed to be ideal; i.e. they do not produce any harmonic. Therefore, they were modeled based on as descried on section II.2.
4- The structure of each component of the network is symmetrical.

IV. Conversion of the Entire Network

In this section, harmonic analysis is performed considering conversion of the entire network. As previously mentioned, if harmonic effects are neglected, usually the criteria used to make a decision on the best type of network conversion are total loss of the network and desirable limits of buses voltages.

The total loss of the existing 3PSC network is 0.099 MW that is changed to 0.195 MW and 0.523 MW by 3PDC or 6PSC conversion of the entire network, respectively. The voltage of buses for both conversions is shown in Fig. 3. It is obvious the buses voltages in both conversions are remained at the desirable limits. Because of the increased capacitance of 6PSC than to 3PDC line, the voltage exceeds at some buses in 6PSC conversion. However, considering total loss of the network, 3PDC conversion would be the better option for network conversion.

IV.1. Harmonic Frequency Scan

The results achieved by frequency scan at buses #1 and #4 are shown in Figs. 4. This Figures represent the magnitude of driving impedance at the mentioned buses. Due to the results, number of resonances and magnitude of driving impedance are different for 3PDC and 6PSC conversions. Once can conclude the number of resonances occurred in 6PSC network is more than 3PDC network.

Also, compared to 3PDC network, magnitude of high frequency impedances is increased in 6PSC network leading to less propagation of high frequency disturbances along the system. In 6PSC network, considering the inductance of the conversion transformers placed in any lines and connected to any bus, the inductive part of driving impedance is dominant leading to increase of the impedance magnitude with the frequency, at high frequency harmonics.

TABLE I
BACK IMPEDANCE IN STATIONS

Station	Khorramaba	Kermanshah	Shomalk	Karkh	Karun	Choghada	Jesfeh	Omidi
R_0, Ω	72	30.4	8.96	7.52	0.96	2.4	0.96	7.2
X_0, Ω	320	88.65	32.32	32.32	11.2	14.4	8.32	24.32
R_+, Ω	24.48	2.88	0.96	0.96	0.48	1.12	0.48	0.96
X_+, Ω	215.65	32.96	15.04	14.40	8.16	15.2	7.68	10.72

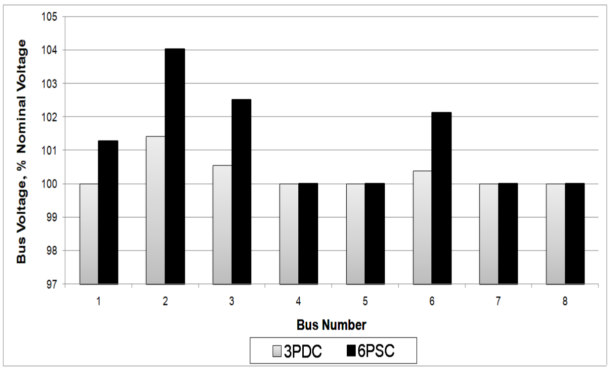
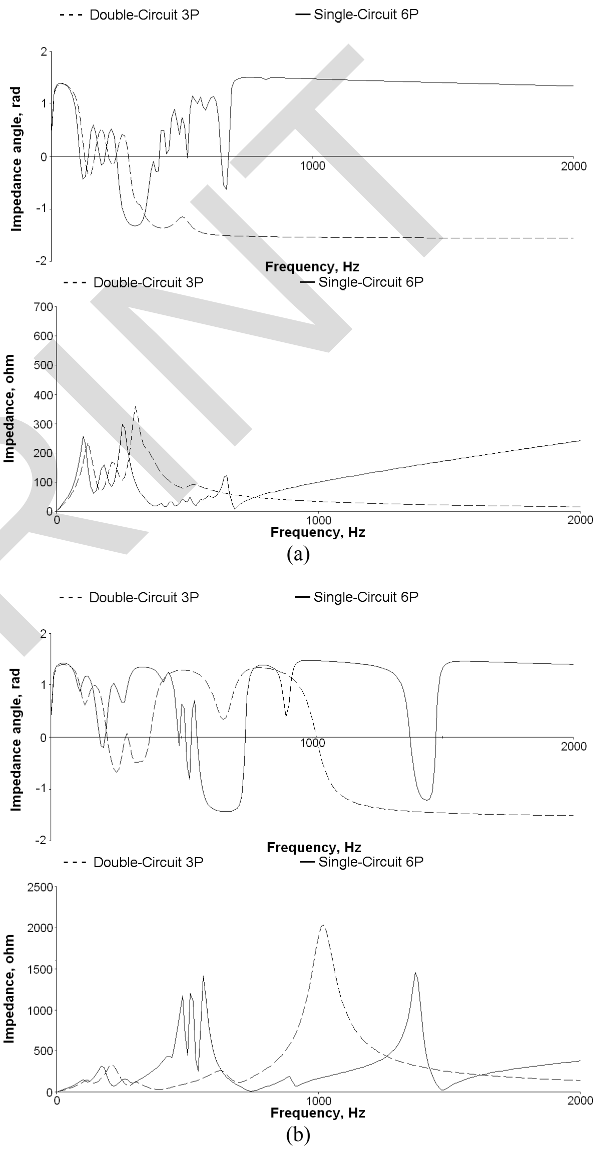


Fig. 3. Magnitude of buses voltage in conversion of the entire network

IV.2. Harmonic Load Flow

In order to perform harmonic load flow, the simulations were executed for two harmonic load types. In order to go through this, firstly it was assumed that a PWM ASD and a 6-pulse rectifier load are connected at bus#1 and bus#4, respectively. These two loads are modeled by a harmonic current source. After executing simulations, for both heavy and light load conditions, TIF value of the lines current and RMS and THD values of the buses voltage are calculated. The results are shown in Tables II-III. According to results, in 6PSC network with a PWM ASD load, voltage THD of all buses is dramatically lower than those in 3PDC network, for both heavy and light load conditions. However, in most of the cases, TIF of lines current in 6PSC network is much greater than those in 3PDC network. However, total loss of 3PDC and 6PSC networks, considering the harmonics effects, is changed to 0.194 MW and 0.519 MW, respectively. It is evidence that total loss of the network is somewhat different from those evaluated for the condition, in which all the harmonics were neglected. This should be born in mind for any optimization algorithm in order to minimize total loss of the network. In the next stage, it is assumed that an EAF load is connected at bus#1 together with a 6-pulse rectifier load connected at bus#4. EAF load is modeled by a harmonic voltage source.

All the previous studies are performed and TIF of lines current and RMS and THD of buses voltage are calculated, shown in Tables IV-V.



Figs. 4. Driving impedance at buses #1 and #4 for both 3PDC and 6PSC conversions (a) Driving impedance at bus#1, (b) Driving impedance at bus#4

TABLE II
TIF OF LINE CURRENT AT 3PDC AND 6PSC NETWORK CONNECTED TO PWM ASD LOAD

	Line	1-2	2-3	3-4	1-5	5-6	2-6	3-7	6-8
Full Load	3PDC Network	45	109	70	151	145	61	22	60
	6PSC Network	124	166	260	812	403	297	565	1191
Light Load	3PDC Network	25	81	39	120	109	45	15	36
	6PSC Network	68	80	100	724	226	98	320	593

TABLE III
RMS AND THD OF BUS VOLTAGE AT 3PDC AND 6PSC NETWORK CONNECTED TO PWM ASD LOAD

	Full Load				**Light Load**			
	3PDC Network		**6PSC Network**		**3PDC Network**		**6PSC Network**	
Bus no.	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**
1	100.57	10.65	101.32	3.24	100.38	8.74	103.06	1.90
2	101.65	6.52	104.04	1.13	101.47	6.19	104.42	0.61
3	100.64	4.21	102.51	0.63	100.75	3.95	102.91	0.35
4	100.09	4.20	100.01	1.63	100.08	4.01	100.01	1.03
5	100.07	3.63	100. 02	1.91	100.03	2.43	100.28	1.17
6	100.63	6.72	102.16	2.70	100.65	5.57	102.61	1.62
7	100.13	5.15	100.07	3.62	100.12	4.86	100.04	2.74
8	100.21	6.54	100.09	4.14	100.15	5.43	100.04	2.68

TABLE IV
TIF OF LINE CURRENT AT 3PDC AND 6PSC NETWORK CONNECTED TO EAF LOAD

	Line	**1-2**	**2-3**	**3-4**	**1-5**	**5-6**	**2-6**	**3-7**	**6-8**
Full Load	3PDC Network	79	108	67	204	193	73	23	83
	6PSC Network	592	606	634	398	219	388	650	492
Light Load	3PDC Network	76	82	42	209	187	64	19	69
	6PSC Network	589	602	538	408	192	299	648	363

TABLE V
RMS AND THD OF BUS VOLTAGE AT 3PDC AND 6PSC NETWORK CONNECTED TO EAF LOAD

		Full	**Load**			**Light**	**Load**	
	3PDC	**Network**	**6PSC**	**Network**	**3PDC**	**Network**	**6PSC**	**Network**
Bus no.	**Voltage RMS, %**	**VoltageTHD, %**	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**
1	100.85	13.08	102.11	12.91	100.85	13.08	103.87	12.69
2	101.76	8.01	104.59	10.41	101.67	8.76	104.94	10.00
3	100.76	6.44	102.85	8.11	100.98	7.86	103.27	8.44
4	100.20	6.37	100.97	13.97	100.30	7.73	100.94	13.73
5	100.20	6.29	100.78	12.54	100.23	6.85	100.92	11.36
6	100.80	8.89	103.06	13.57	100.97	9.68	103.45	12.94
7	100.26	7.17	110.28	46.50	100.39	8.79	115.51	57.82
8	100.37	8.62	101.14	15.16	100.44	9.41	100.99	14.08

The above results show that at 6PSC network with an EAF load, TIF of lines current and THD of buses voltage are mostly more than the values obtained for 3PDC network.

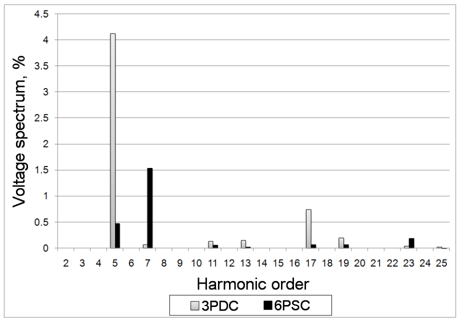
It could be concluded that in network conversion, variation of voltage THD depends on the type of harmonic sources existed in the network. Therefore, from the power quality point of view, the connected load would be also important to adopt the best option for network conversion.

In Figs. 5, considering a PWM ASD or EAF load connected at bus#1, harmonic spectrum of voltage of bus#4, at where a 6-pulse rectifier load is connected, is plotted as a percent of the fundamental component.

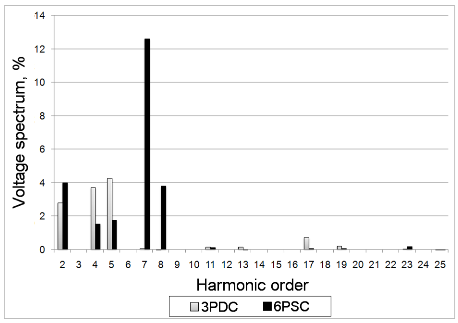
Although, standards specify up to the 50th harmonic order, however in the most cases, it is proper to consider the harmonic orders up to 25th [13].

The result shows that the harmonics magnitude would also be different and dependent on the load type.

However, by neglecting harmonics, 3PDC network is a better option for conversion than to 6PSC network. Considering harmonics, 6PSC conversion maybe the better option, due to its decreased value of voltage THD caused by current source type of harmonic loads.



(a)



(b)

Figs. 5. Harmonic voltage spectrum of bus#4 for both 3PDC and 6PSC networks (a) PWM ASD load at bus#1, (b) EAF load at bus#1

V. Conversion of One of the Existing Lines to 3PDC & 6PSC

In the previous section, the entire network was converted to 3PDC and 6PSC network. However, in any optimization algorithm all the possible options for conversion should be considered; as conversion of one or some transmission lines to 3PDC or 6PSC lines, instead of conversion of the entire network, may lead to better result. Therefore, in this section, conversion of one of the existing 3PSC lines to 3PDC and 6PSC line is investigated. The constraints to find the best converted line were total loss of the network and voltage limits of buses. The total loss of the network caused by conversion of one of the existing lines is tabulated in Table VI. Considering the obtained results, it could be concluded that, by neglecting the harmonics, conversion of line 2-6 (line between buses #2 and #6) is the best option for 3PDC or 6PSC conversion; as the voltage limits are satisfied, all buses are at 100% nominal voltage (400 kV), and minimum network loss is met equal to 0.079 MW and 0.082 MW for 3PDC and 6PSC conversion, in full load condition, respectively.

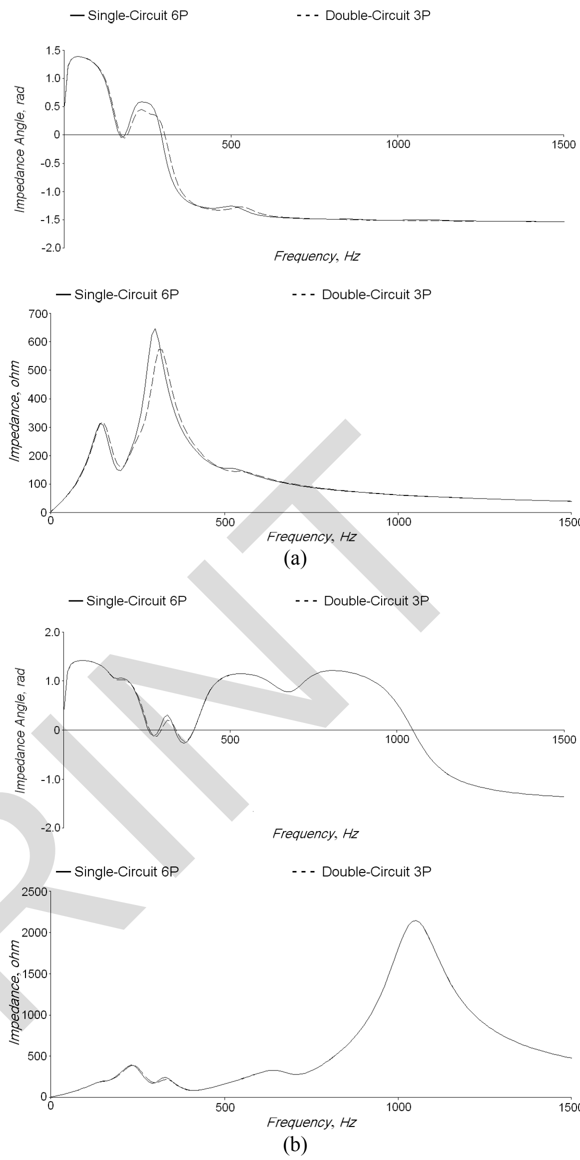
In the following, by considering the conversion of line 2-6, the harmonic analysis is as previously performed and the obtained results are discussed.

V.1. Harmonic Frequency Scan

Figs. 6 represent the angle and magnitude of driving impedance at buses #1 and #4, once line 2-6 is converted to 3PDC and 6PSC line. The gathered results show that the resonance condition and magnitude of high-frequency impedances are nearly the same for both conversions. As the loads #1 and #4 are directly connected at buses, then driving impedance at relevant buses is nearly the same for both conversions.

V.2. Harmonic Load Flow

For the conversion of line 2-6, in which a PWM ASD and 6-pulse rectifier load are connected at buses #1 and #4, respectively; TIF of lines current and RMS and THD of buses voltage are presented in Tables VII, VIII, for both heavy and light load conditions. Based on the obtained results, for both heavy and light load conditions, in the network with PWM ASD and 6-pulse rectifier load types, TIF of lines current is varied and THD of buses voltage is mostly lower in 6PSC conversion as compared to 3PDC conversion. Also, total loss of the network, in which line 2-6 is converted to 3PDC and 6PSC lines, is equal to 0.077 MW and 0.079 MW, respectively. Finally, all the pervious simulations are performed with an EAF load and a 6-pulse rectifier load connected at bus#1 and bus#4, respectively. The results, presented in Tables IX, X, show that in this state, THD of buses voltage is mostly lower and TIF of lines current is mostly greater in 6PSC than 3PDC conversion.



Figs. 6. Driving impedance of network (line 2-6 is converted to 3PDC and 6PSC line) (a) Driving impedance at bus#1, (b) Driving impedance at bus#4

Moreover, considering PWM ASD or EAF load connected at bus#1, the harmonic spectrum of voltage at bus#4, at where a 6-pulse rectifier load is connected, is shown in Figs. 7 as a percent of the fundamental component.

As a consequence, if harmonics are neglected, 3PDC conversion of one of the lines is a better conversion; while by considering harmonics, 6PSC conversion may be worth.

TABLE VI
TOTAL LOSS OF NETWORK (IN FULL LOAD CONDITION), IN MW, BY CONVERSION OF ONE OF THE EXISTING LINES TO 3PDC OR 6PSC LINE

Converted line	1-2	2-3	3-4	1-5	5-6	2-6	3-7	6-8
3PDC	0.091	0.097	0.097	0.093	0.095	0.079	0.100	0.097
6PSC	0.119	0.119	0.099	0.098	0.098	0.082	0.101	0.098

TABLE VII
TIF OF LINE CURRENT FOR THE NETWORK CONNECTED TO PWM ASD LOAD–
ONLY LINE 2-6 IS CONVERTED TO A 3PDC AND 6PSC LINE

	Line	**1-2**	**2-3**	**3-4**	**1-5**	**5-6**	**2-6**	**3-7**	**6-8**
Full Load	3PDC Network	680	53	476	545	195	73	129	108
	6PSC Network	670	89	478	545	185	120	116	100
Light Load	3PDC Network	349	31	259	347	105	41	79	55
	6PSC Network	334	37	261	356	92	64	64	54

TABLE VIII
RMS AND THD OF BUS VOLTAGE FOR THE NETWORK CONNECTED TO PWM ASD LOAD–
ONLY LINE 2-6 IS CONVERTED TO A 3PDC AND 6PSC LINE

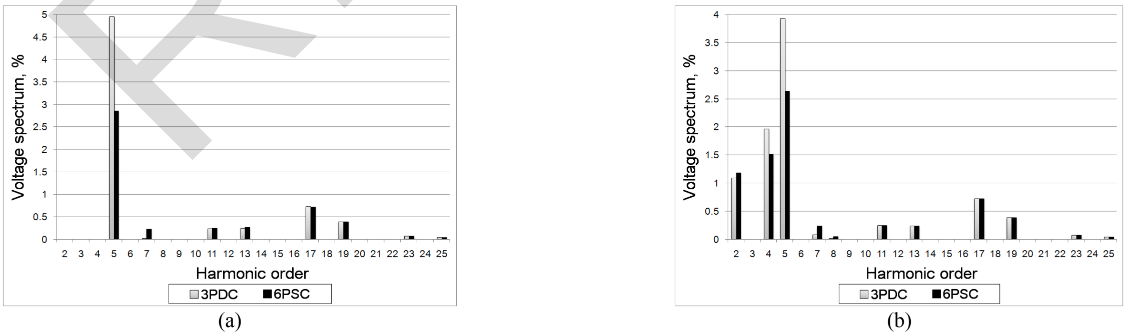
	Full Load				Light Load			
	3PDC Network		**6PSC Network**		**3PDC Network**		**6PSC Network**	
Bus no.	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**
1	101.19	15.47	101.26	15.93	100.66	11.50	100.6	10.98
2	100.18	6.04	100.09	4.13	100.15	5.47	100.05	3.28
3	100.16	5.66	100.06	3.39	100.16	5.65	100.05	3.01
4	100.13	5.04	100.05	3.02	100.13	5.10	100.04	2.74
5	100.16	5.58	100.22	6.59	100.07	3.79	100.11	4.62
6	100.22	6.66	100.10	4.39	100.17	5.76	100.21	3.16
7	100.18	6.08	100.07	3.66	100.19	6.15	100.05	3.31
8	100.18	5.98	100.08	3.96	100.13	5.19	100.04	2.87

TABLE IX
TIF OF LINE CURRENT FOR THE NETWORK CONNECTED TO EAF LOAD-
ONLY LINE 2-6 IS CONVERTED TO A 3PDC AND 6PSC LINE

	Line	1-2	2-3	3-4	1-5	5-6	2-6	3-7	6-8
Full Load	3PDC Network	213	34	470	131	178	59	119	96
	6PSC Network	221	46	471	155	168	104	117	79
Light Load	3PDC Network	175	32	257	131	132	43	77	79
	6PSC Network	177	40	258	174	126	96	68	73

TABLE X
RMS AND THD OF BUS VOLTAGE FOR THE NETWORK CONNECTED TO EAF LOAD–
ONLY LINE 2-6 IS CONVERTED TO A 3PDC AND 6PSC LINE

	Full Load				**Light Load**			
	3PDC Network		**6PSC Network**		**3PDC Network**		**6PSC Network**	
Bus no.	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**	**Voltage RMS, %**	**Voltage THD, %**
1	100.85	13.08	100.85	13.08	100.85	13.08	100.85	13.08
2	100.15	5.52	100.10	4.34	100.19	6.12	100.12	4.80
3	100.12	4.83	100.07	3.61	100.20	6.33	100.10	4.37
4	100.11	4.62	100.06	3.40	100.17	5.78	100.08	3.94
5	100.13	5.03	100.16	5.68	100.12	4.86	100.18	5.97
6	100.19	6.10	100.11	4.62	100.24	6.93	100.29	5.05
7	100.13	5.02	100.07	3.72	100.22	6.70	100.10	4.55
8	100.15	5.45	100.08	4.12	100.20	6.26	100.10	4.58



Figs. 7. Harmonic voltage spectrum of bus#4 for both conversions types of line 2-6 (a) PWM ASD load at bus#1, (b) EAF load at bus#1

VI. Conclusion

In order to increase the power transfer capability of the existing network to meet the increasing energy demand, conversion of 3PSC lines to 3PDC and 6PSC lines is a well known method. Constraints that may be used to decide on the optimal option of conversion are usually total loss of the network and desirable voltage limits while the system harmonics are neglected.

However, harmonics can affect on the network loss and buses voltage and also deteriorate the power quality of the power systems.

In this paper, a harmonic analysis in the case of conversion of 3PSC network to 3PDC and 6PSC networks is performed. The analysis is accomplished by conversion of the entire network and just one of the existing lines of the network, separately.

The results of this research show that, by considering the harmonics or omitting their effects, the criteria needed to make a decision and also the optimal option for network conversion are changed.

Due to studies done in this paper, currents TIF and voltages THD are dependent on the conversion type, i.e. 3PDC and 6PSC conversions, and also may be dependent on the type of harmonic sources existed in network. A further work is required to investigate the exact dependence between type of the harmonic sources and THD, TIF and RMS values in network conversion.

Beside, analysis of results of frequency scan show that by converting the entire network to 6PSC network, the resonances are more and the magnitude of high frequency impedances is greater compared to 3PDC conversion. This leads to less propagation of high frequency disturbances along a network with 6PSC lines.

As a consequence, in any optimization algorithm, in order to obtain the correct results, the power quality indices together with total loss of the network and voltage limits of buses should be considered. A further work is also required to study the economic together with the technical criteria on the best option adopted for network conversion.

Appendix A

The detailed data of the study system is tabulated in Tables A1, A2 and A3.

TABLE A1
DETAILED DATA OF CONVERSION TRANSFORMERS AND GENERATOR STEP-UP TRANSFORMER

Transformer type	Conversion transformer	Generator transformer
S, MVA	400	1500
Z_+, p.u.	0.08	0.08
X_+/R_+	1000	1000
Z_0, p.u.	0.08	0.08
X_0/R_0	100	100
Winding turn ratio	400/400	13.8/400

TABLE A2
LINES DATA

Line type	3PSC	3PDC	6PSC
R_+ @ 20˚C, Ω/km	0.0314	0.01858	0.03662
R_0 @ 20˚C, Ω/km	0.31015	0.31468	0.35655
R_+ @ 50˚C, Ω/km	0.03484	0.01996	0.03942
R_0 @ 50˚C, Ω/km	0.31823	0.32947	0.37405
X_+, Ω/km	0.42393	0.23243	0.39081
X_0, Ω/km	1.11578	0.985	1.414
Y_+, Ω/km	3.87283	7.10741	4.31533
Y_0, Ω/km	2.56181	2.88508	3.11187

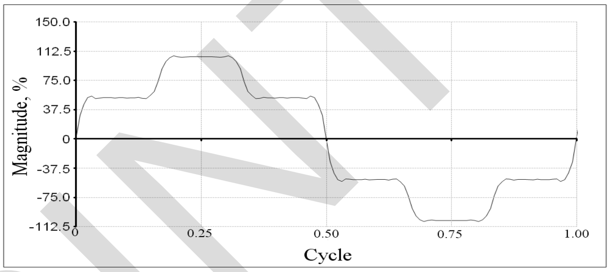
Note: Negative sequence impedance and admittance of transmission lines are equal to their positive sequence ones.

TABLE A3
LOADS DATA (IN FULL LOAD CONDITION)

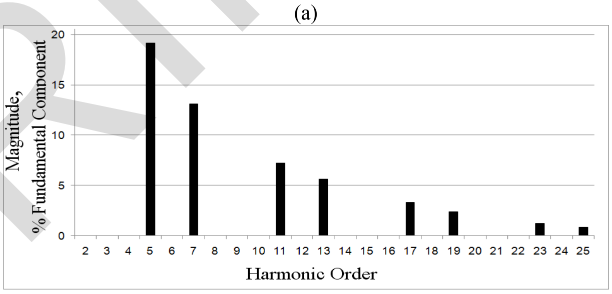
Bus no.	Dynamic load		Static load	
	P, MW	Q, MVAr	P, MW	Q, MVAr
1	148.5	80.152	49.5	26.72
2	105.6	56.996	35.2	18.999
3	96.8	52.247	13.2	7.125
4	67.497	36.43	15.577	8.407
5	167.024	90.15	61.776	33.343
6	90.851	49.036	11.229	6.061
7	80.036	43.199	14.124	7.623
8	100.232	54.102	17.688	9.547

Appendix B

The waveforms and harmonic spectrums of 6-pulse rectifier, PWM ASD and EAF harmonic loads, studied in this paper, are shown in Figs. 1B, 2B and 3B.

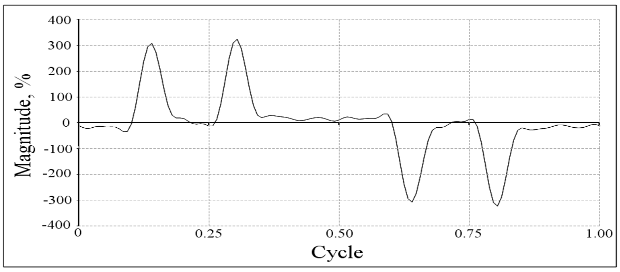


(a)

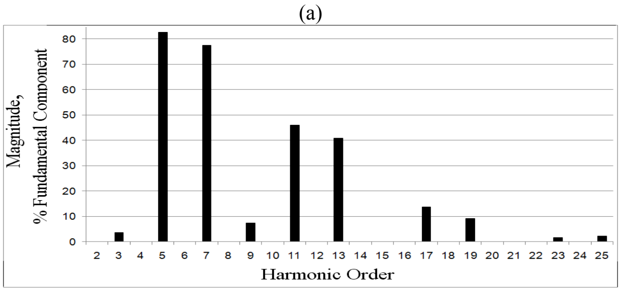


(b)

Figs. 1B. 6-pulse rectifier load
(a) Current waveform, (b) Harmonic spectrum

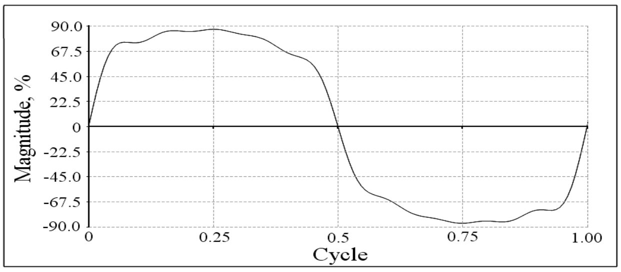


(a)

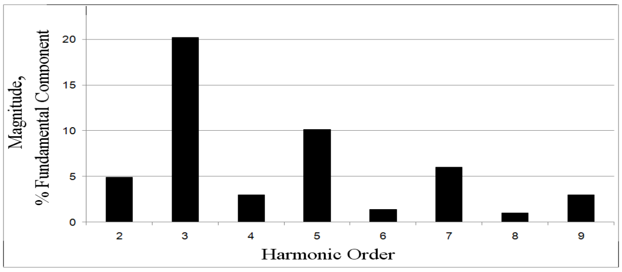


(b)

Figs. 2B. PWM ASD load
(a) Current waveform,(b) Harmonic spectrum



(a)



(b)

Figs. 3B. EAF load
(a) Current waveform, (b) Harmonic spectrum

References

[1] Barthold, L. O., and Barnes, H. C. "High phase order power transmission," CIGRE study committee Report, no. 31, 1972.

[2] A. P. Apostolov, and R. G. Raffensperger, Relay protection for faults on NYSEG'S six-phase transmission line, *IEEE Transactions on Power Delivery, Vol. 11(*Issue 1*):191-196, August 1996.*

[3] M. R. Ahmad, *Static and dynamic impacts of six phase power transmission system,* M.Sc. thesis, Dept. Elect. Eng., Tech. Univ. of Malaysia, Malaysia, 2007.

[4] Venkata, S. S. "Reliability and economics analysis of higher phase order electric transmission system," Final Report, no. 74 ENGR 10400, 1977.

[5] T. L. Landers, R. J. Richeda, E. Krizauskas, J. R. Stewart, and R. A. Brown, High Phase Order Economics: Constructing A New Transmission Line, *IEEE Transactions on Power Delivery, Vol. 13(*Issue 4*):1521-1526, October 1998.*

[6] *M. Mirzaie, M. Yazdani-Asrami, S. B. Sadati, and A. Shayegani Akmal,* Impacts of non-sinusoidal load currents on distribution transformer losses-Part I: Theoretical aspects and finite element based simulation**,** *International Review of Electrical Engineering (IREE), Vol. 6(*Issue 5*): October 2011.*

[7] M. D. Kusljevic, Adaptive Resonator-Based Method for Power System Harmonic Analysis, *IET Sci. Meas. Technol., Vol. 2(*Issue 3*):177–185, March 2008.*

[8] *J. Alahuhtala, J. Virtakoivu, T. Viitanen, M. Routimo, and H. Tuusa,* Implementing an active filter function with vienna rectifier, *International Review of Electrical Engineering (IREE), Vol. 5(*Issue 2*): 371-379, April 2010.*

[9] H. Liao, Power system harmonic state estimation and observability analysis via sparsity maximization, *IEEE Transactions on Power Systems, Vol. 22(Issue 1):15-23, January 2007.*

[10] R. Shariatinasab, M. Akbari, Harmonic analysis of power systems in order to network conversion, *IEEE Power & Energy Conference (PECon), pp. 974-979, Kuala Lumpur, Malaysia, November/ December 2010.*

[11] IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Std. 519-1992, 1993.

[12] W. Xu, Component Modeling Issues for Power Quality Assessment, *IEEE Power Engineering Review, Vol. 21(*Issue 11*):12-17, November 2001.*

[13] J. Arrillaga, N. R. Watson, *Power System Harmonics* (John Wiley & Sons, 2003)

[14] D. Thukaram, H. P. Khincha, B. RaviKumar, Harmonic minimization in the operation of static VAR compensators for unbalanced reactive power compensation, *International Conference on Power System Technology (PowerCon), Singapore, pp. 328-334, November 2004.*

[15] N. Yousefpoor, B. Vahidi, and S. H. Fathi, Voltage and current harmonics reduction in series-connected rectifiers for HVDC transmission system, *International Review on Modelling and Simulations (IREMOS), Vol. 3* (Issue 2*): 255-264, April 2010.*

[16] W. Xu, Z. Huang, Y. Cui, and H. Wang, Harmonic Resonance Mode Analysis, *IEEE Transactions on Power Delivery, Vol. 20(*Issue 2*):1182-1190, April 2005.*

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