# Harmonic Analysis of Power Systems in order to Network Conversion

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***Abstract*—Conversion of three-Phase Single-Circuit (3PSC) network to three-Phase Double-Circuit (3PDC) and six-Phase Single-Circuit (6PSC) network is a well known method to increase the power transfer capability of the network to meet the increasing energy demand. The most significant constraints maybe used to decide on the optimal alternative, are total loss of the network and desirable voltage limits, while harmonics are omitted. However, harmonic impacts may cause damage to instruments, lead to undesirable power quality and increase total loss of the network. Thereby, in order to obtain the accurate result or adopting an optimal alternative for network conversion, harmonics should be considered. In this paper, harmonic analysis due to conversion of a 3PSC network to 3PDC and 6PSC network is performed. In the study, conversion of entire and one line of the network are analyzed, separately. The results show that suitable alternative for network conversion, with or without considering the effects of harmonics, is different. Also TIF of current is dependent of type of conversion and is different for 3PDC and 6PSC systems; but THD of voltages completely depends on the type of harmonic source in the network. However, analysis of frequency scan results shows that the number of resonances is more in 6PSC conversion than 3PDC counterpart. Also 6PSC conversion leads to less propagation of disturbances along the system during high frequency transients such as lightning surges.**

***Keywords*—Harmonic Analysis, Harmonic Frequency Scan, Six-Phase System, THD, TIF**

## I. Introduction

Electricity is considered as the driving force for a country, which is undergoing rapid industrialization. Traditionally, the need for increasing power transmission capability and more efficient use of right of way (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 existing ROWs. High phase order (HPO) transmission, using more than three phases, was conceived as a means for increasing the power transfer capability of 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 at the same time, it responds to the concerns related to electromagnetic fields [2, 3]. Three-phase line can be easily converted to a six-phase line using conversion transformers, which make the required 60° phase shift at six-phase side [4-5].

In [6-11], it had been shown that the six-phase transmission system can provide the same power transfer capability with lower ROW or can transfer 73% more power for the same ROW compared to the three-phase double-circuit system. Some other advantages of the six-phase transmission system over conventional 3PDC system are smaller structure [5], lower corona and field effects [11], lower insulation requirement [6], better stability margin [11] and better voltage regulation [4, 5].

In [12], results illustrate that the use of six-phase transmission can be a cost effective solution. In other words, the cost penalty for constructing a new six-phase line versus a three-phase line with the same voltage level is not excessive, particularly if physical constraints exist. The high cost of terminals, due to application of conversion transformers, is offset by reduced tower and lower foundation costs, ROW cost and losses [5].

Although conventional three-phase lines conversion to 3PDC and 6PSC transmission lines results in many advantages, e.g. increased transmission capability, in order to achieve accurate results or adopt the best solution, other aspects such as harmonic effects should be considered in this conversion.

The presence of harmonics in a power system can give rise to a variety of problems including equipment overheating, reduced power factors, deteriorating performance of electrical equipment, the incorrect operation of protective relays, interference with communication devices, and in some cases circuit resonance to cause electric apparatus dielectric failure. Even worse, 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. So, harmonics problem has come into prominence to electric power industry and consumers of electric energy, due to the ever-increasing usage of electronic devices and equipment in power systems.

Thereby, harmonic study, as one of the significant studies to determine and optimize the power system, should be made. In this paper in order to decide on better alternative, the harmonic impacts of conversion of 3PSC to 3PDC and 6PSC system are studied. The investigation is performed with and without considering the harmonics effects. To investigate the harmonics two analytical

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methods, i.e. harmonic load flow and harmonic frequency scan are considered. In this work, the entire and one-line conversion of the existing 3PSC network to 3PDC and 6PSC is investigated.

## II. Harmonic Analysis

Because of the wide and ever-increasing applications of power electronic devices, such as variable speed drives (VFD), uninterruptible power supplies (UPS), static power converters and etc., power system voltage and current quality has been severely affected with the resultant harmonics. In addition to electronic devices, some other non-linear loads, or devices including saturated transformers, arc furnaces, fluorescent lights, and cycloconverters are also responsible for deterioration in power system quality.

Harmonic current makes interference with communication devices; however, harmonic voltage is the most significant problem.

### A. Harmonic Indices

The effect of harmonics is usually measured in terms of several indices that are defined as below [13].

1) Root Mean Square (RMS): This is the square root of the sum of the squares of the magnitudes of the fundamental plus all harmonics in the system. The total RMS is determined by:

$$RMS = \sqrt{\sum_{i=1}^{\infty} F_i^2} \tag{1}$$

Where, $F_i$ is the amplitude of the $i^{th}$ harmonic.

2) Total Harmonic Distortion (THD): THD is the most popular index to measure the level of harmonic distortion to voltage and current. However, voltage THD is more significant index than current THD. It is determined by:

$$THD = \frac{\sqrt{\sum_{i=2}^{\infty} F_i^2}}{F_1} \tag{2}$$

Where, $F_1$ is the amplitude of the fundamental component.

3) Telephone Influence Factor (TIF): TIF is a variation of the 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. Normally, the current TIF has a more significant impact on adjacent communication systems. The TIF is determined by:

$$TIF = \frac{\sqrt{\sum_{i=1}^{\infty} (W_i F_i)^2}}{\sqrt{\sum_{i=1}^{\infty} F_i^2}} \tag{3}$$

Where, $W_i$ is the TIF weighting factor. The values for the weighting factors for different harmonic frequencies are given in the IEEE Standard 519 [13].

### B. Harmonic Frequency Scan

One particular concern with the harmonics is resonance condition in power system. Due to the existence of both inductive and capacitive components in the system, at certain frequencies, resonance condition might occur at some buses. Once the resonance occurs at the bus where harmonic current is injected into the system, overvoltage and overcurrent condition are issued.

The frequency scan method is the best tool to investigate the system resonance. It calculates and plots the magnitudes and phase angles of bus impedance over a specified frequency range; thus any parallel resonance condition and its triggering frequency can be clearly identified. The study of frequency scan also allows adjusting the parameters of harmonic filters [14].

### C. Harmonic Load Flow

Firstly, harmonic load flow study carries out a load flow calculation at the fundamental frequency. The obtained results set the initial values for voltage and currents that are used later to calculate different harmonic indices. Then, for each harmonic frequency at which any harmonic source exists in the system, a direct load flow is accomplished by means of current injection method. The impedance of system's components is adjusted based on the harmonic frequencies and the type of component. Once harmonic load flow is executed, the harmonic components of the bus voltages and branch currents are found and harmonic indices are obtained accordingly.

## III. Case Study

The schematic diagram of case study is shown in Fig. 1. The selected network consists of 3 generators, 3 transformers, 3 load buses and 6 transmission lines that all are 3PSC lines. In order to perform harmonic analysis, the entire network and one line of the network is converted to 3PDC and 6PSC system, separately.

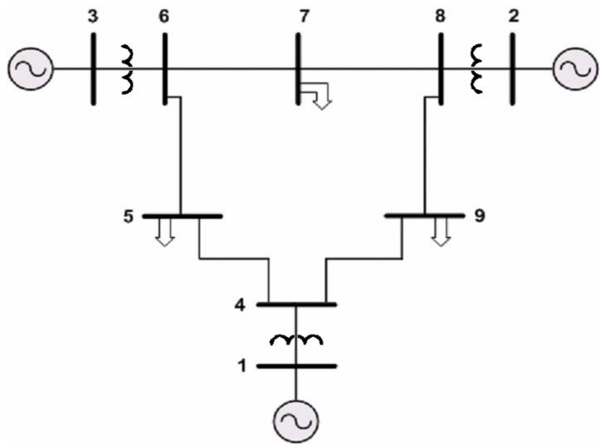


Figure 1. Schematic diagram of case study

There are some common connections and combinations that can be used to form a three to six-phase conversion transformer [4]. In this paper, Δ-Y & Δ-Inverted Y connection was selected, Fig. 2. One of each pair of transformers has reverse polarity to obtain the required 60° phase shift. Also in this study, it was assumed that all the generators and transformers are ideal and without harmonics. However, the load connected at bus 5 is assumed to be the harmonic source.

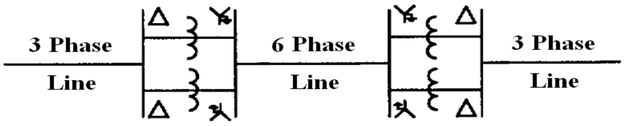


Figure 2. Connections of the phase conversion transformer

## IV. Conversion of the Entire Network

If harmonic effects are neglected, the criteria used to decide on the best conversion for existing network are total loss and desirable voltage limits of buses (±5% of rated voltage). Total loss of the existing 3PSC network is equal to 1.4991 MW that is changed to 0.9993 MW and 1.0046 MW by converting the entire network to a 3PDC and 6PSC network, respectively. Since bus voltages in both conversions are remained in desirable limits, 3PDC network due to its less loss compared to 6PSC network would be the better alternative.

### A. Harmonic Frequency Scan

The results achieved by frequency scan at buses 5, 7 and 9 are shown in Figs. 3-5. These results are the magnitude of driving impedance at each bus.

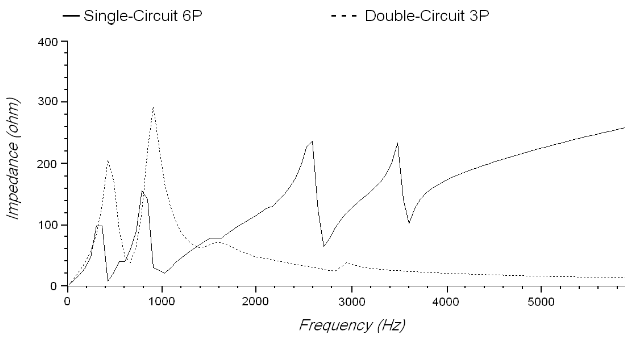


Figure 3. Driving impedance at bus 5 for 3PDC & 6PSC conversion

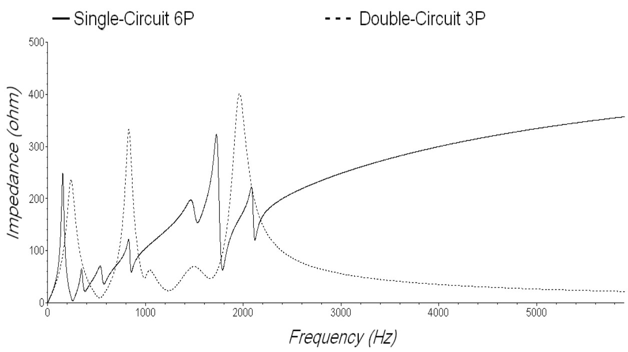


Figure 4. Driving impedance at bus 7 for 3PDC & 6PSC conversion

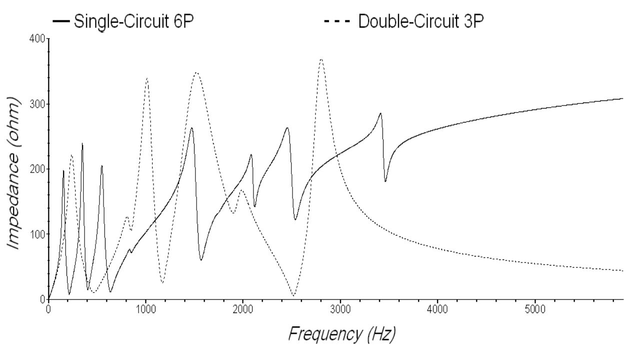


Figure 5. Driving impedance at bus 9 for 3PDC & 6PSC conversion

The results show that number of resonances and resultant values of impedance are different in 3PDC and 6PSC network. However, resonances occurred in 6PSC network are more than 3PDC network. Also, the magnitude of low-frequency impedances of bus in 6PSC network is less than those in 3PDC network. Therefore, with existence of the same harmonic source, amplitude of harmonic voltages in 6PSC network will be lower compared to those in 3PDC network. Moreover, magnitude of high-frequency impedances is increased at 6PSC network than 3PDC conversion. This effect leads to less propagation of disturbances along the system during high-frequency transients such as lightning surges.

### B. Harmonic Load Flow

Firstly, it is assumed that the load connected at bus 5 is a 6 pulse VFD. This load is modeled by a current source. RMS and TIF values of line current and RMS and THD values of bus voltages are shown in Tables I-IV.

TABLE I.
RMS and TIF of Line Currents at 3PDC Network with a 6 Pulses VFD Load

| Line No. | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 4-9 |
|---|---|---|---|---|---|---|
| **RMS (A)** | 200 | 80 | 78 | 194 | 94 | 232 |
| **TIF (%)** | 300 | 675 | 767 | 269 | 465 | 267 |

TABLE II.
RMS and THD of Bus Voltages at 3PDC Network with a 6 Pulse VFD Load

| Bus No. | RMS Voltage (%) | THD (%) |
|---|---|---|
| **1** | 100.06 | 3.33 |
| **2** | 100.1 | 4.52 |
| **3** | 100.06 | 3.33 |
| **4** | 100.36 | 5.98 |
| **5** | 100.55 | 6.45 |
| **6** | 101.03 | 6.7 |
| **7** | 100.72 | 7.24 |
| **8** | 100.69 | 6.9 |
| **9** | 99.97 | 6.27 |

TABLE III.
RMS and TIF of Line Currents at 6PSC Network with a 6 Pulse VFD Load

| Line No. | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 4-9 |
|---|---|---|---|---|---|---|
| **RMS (A)** | 148 | 234 | 68 | 180 | 64 | 122 |
| **TIF (%)** | 62 | 36 | 145 | 40 | 101 | 74 |

TABLE IV.
RMS and THD of Bus Voltages at 6PSC Network with a 6 Pulse VFD Load

| Bus No. | RMS Voltage (%) | THD (%) |
|---|---|---|
| **1** | 100.01 | 1.00 |
| **2** | 100.02 | 1.81 |
| **3** | 100 | 0.85 |
| **4** | 102.03 | 1.38 |
| **5** | 103.17 | 1.62 |
| **6** | 104.57 | 1.23 |
| **7** | 103.29 | 1.74 |
| **8** | 102.88 | 2.23 |
| **9** | 101.64 | 1.23 |

According to results, at 6PSC network with 6 pulse VFD load, THD of bus voltages and TIF of line currents are lower than those calculated at 3PDC network.

Total loss for 6PSC and 3PDC network is shown in Fig. 6. The result shows that total loss of 6PSC network is greater than 3PDC network. The main difference is caused by the phase conversion transformers.

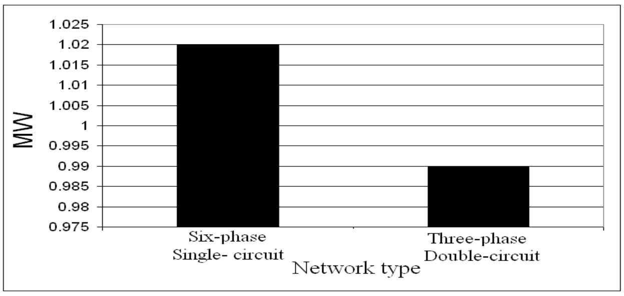


Figure 6. Total loss by converting the existent network to 3PDC and 6PSC network

In the next stage, the load connected at bus 5 is considered an arc furnace load. This type of load is modeled by a voltage source. All the previous studies are performed again. RMS and TIF of line currents and RMS and THD of bus voltages are shown in Tables V-VIII.

TABLE V.
RMS AND TIF OF LINE CURRENTS AT 3PDC NETWORK WITH ARC FURNACE LOAD

| Line No. | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 4-9 |
|---|---|---|---|---|---|---|
| **RMS Current (A)** | 112 | 55 | 54 | 103 | 50 | 123 |
| **TIF (%)** | 209 | 259 | 441 | 203 | 197 | 199 |

TABLE VI.
RMS AND THD OF BUS VOLTAGES AT 3PDC NETWORK WITH ARC FURNACE LOAD

| Bus No. | RMS Voltage (%) | THD (%) |
|---|---|---|
| **1** | 100.27 | 7.41 |
| **2** | 100.67 | 11.57 |
| **3** | 100.36 | 8.45 |
| **4** | 101.07 | 13.3 |
| **5** | 101.19 | 13.3 |
| **6** | 102.25 | 17.02 |
| **7** | 102.16 | 18.52 |
| **8** | 102 | 17.68 |
| **9** | 100.92 | 15.2 |

TABLE VII.
RMS AND TIF OF LINE CURRENTS AT 6PSC NETWORK WITH ARC FURNACE LOAD

| Line No. | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 4-9 |
|---|---|---|---|---|---|---|
| **RMS Current (A)** | 94 | 125 | 70 | 105 | 39 | 85 |
| **TIF (%)** | 133 | 65 | 179 | 111 | 188 | 158 |

TABLE VIII.
RMS AND THD OF BUS VOLTAGES AT 6PSC NETWORK WITH ARC FURNACE LOAD

| Bus No. | RMS Voltage (%) | THD (%) |
|---|---|---|
| **1** | 100.2 | 6.31 |
| **2** | 105.92 | 24.61 |
| **3** | 100.72 | 12 |
| **4** | 102.4 | 8.65 |
| **5** | 103.98 | 12.68 |
| **6** | 106.13 | 17.38 |
| **7** | 105.57 | 21.23 |
| **8** | 105.92 | 24.61 |
| **9** | 102.68 | 14.38 |

The above results show that, at 6PSC network with arc furnace load, TIF of line currents is absolutely lower than those obtained in 3PDC network. However, the value of THD of bus voltages is varied. So that value of THD at some buses is increased and at some decreased. Consequently, apart from the type of harmonic source, TIF of current at 6PSC network will be lower compared to 3PDC network. But the value of THD depends on the type of harmonic source. Therefore considering the harmonic effects, 6PSC conversion would be the better alternative compared to 3PDC conversion for network restructuring. While, neglecting the harmonics, 3PDC network is better. Thus harmonics play an important rule and should be considered in any optimization algorithm in order to achieve the accurate results.

## V. CONVERSION OF ONE LINE TO 3PDC & 6PSC

In pervious section, the entire of existing network was converted to a 3PDC and 6PSC system. However, in any optimization algorithm all the possible alternatives must be considered. Maybe conversion of one or some transmission lines instead of conversion of the entire network leads to better results. Therefore in this section, conversion of one line of the network to 3PDC and 6PSC line is investigated. The constraints are total loss and voltage limits. By means of trial and error approach it was concluded that, if harmonics are neglected, then conversion of line 8-9 (line between buses 8 and 9) is the best option for both 3PDC and 6PSC line conversions.

### *A. Harmonic Frequency Scan*

The result of frequency scan at buses 5, 7 and 9 are shown in Figs. 7-9. These results are the magnitude of driving impedance at each bus.

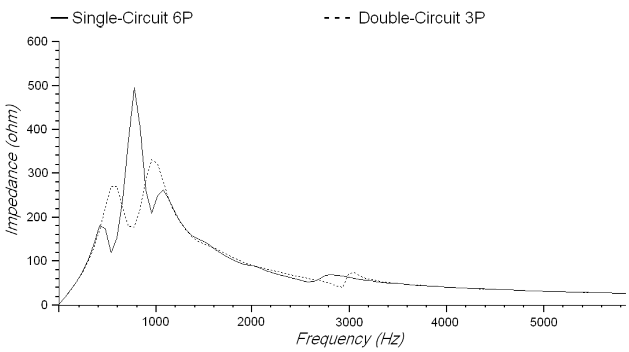


Figure 7. Driving impedance at bus 5 due to conversion of line 8-9 to a 3PDC & 6PSC line

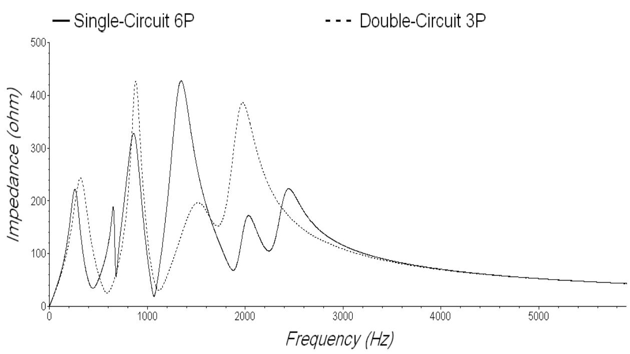


Figure 8. Driving impedance at bus 7 due to conversion of line 8-9 to a 3PDC & 6PSC line

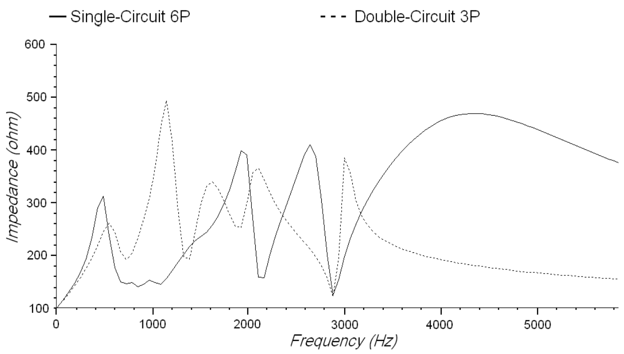


Figure 9. Driving impedance at bus 9 due to conversion of line 8-9 to a 3PDC & 6PSC line

The results show that by conversion of line 8-9 to a 6PSC line, number of resonances is increased compared to 3PDC line. Also, magnitude of high-frequency impedances is greater at 6PSC conversion, compared to 3PDC condition, leading to less propagation of high-frequency transient disturbances such as lightning surges.

## *B. Harmonic Load Flow*

If the load connected at bus 5 is a 6 pulse VFD, then resultant values of RMS and TIF of line currents and RMS and THD of bus voltages are calculated in Tables IX-XII, for conversion of line 8-9.

Based on results for 6 pulse VFD load type, in case of 6PSC conversion, TIF of line currents increase while most values of THD of bus voltages decrease.

TABLE IX.
RMS AND TIF OF LINE CURRENTS (CONVERSION OF LINE 8-9 TO 3PDC LINE), 6 PULSE VFD LOAD

| Line No. | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 4-9 |
|---|---|---|---|---|---|---|
| RMS Current (A) | 211 | 52 | 82 | 179 | 106 | 218 |
| TIF (%) | 276 | 804 | 545 | 172 | 195 | 241 |

TABLE X.
RMS AND THD OF BUS VOLTAGES (CONVERSION OF LINE 8-9 TO 3PDC LINE), 6 PULSE VFD LOAD

| Bus No. | RMS Voltage (%) | THD (%) |
|---|---|---|
| 1 | 100.14 | 5.27 |
| 2 | 100.2 | 6.32 |
| 3 | 100.11 | 4.75 |
| 4 | 99.45 | 9.58 |
| 5 | 99.4 | 12.27 |
| 6 | 100 | 9.69 |
| 7 | 99.33 | 10.27 |
| 8 | 99.58 | 9.79 |
| 9 | 98.75 | 9.8 |

TABLE XI.
RMS AND TIF OF LINE CURRENTS (CONVERSION OF LINE 8-9 TO 6PSC LINE), 6 PULSE VFD LOAD

| Line No. | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 4-9 |
|---|---|---|---|---|---|---|
| RMS Current (A) | 201 | 80 | 81 | 198 | 32 | 238 |
| TIF (%) | 767 | 1838 | 1194 | 676 | 1272 | 578 |

TABLE XII.
RMS AND THD OF BUS VOLTAGES (CONVERSION OF LINE 8-9 TO 6PSC LINE), 6 PULSE VFD LOAD

| Bus No. | RMS Voltage (%) | THD (%) |
|---|---|---|
| 1 | 100.12 | 4.84 |
| 2 | 100.18 | 5.94 |
| 3 | 100.2 | 6.29 |
| 4 | 99.77 | 8.77 |
| 5 | 100.16 | 15.02 |
| 6 | 100.75 | 12.77 |
| 7 | 99.91 | 9.37 |
| 8 | 100.36 | 9.13 |
| 9 | 99.27 | 8.75 |

Also, total loss of the network by conversion of line 8-9 is shown in Fig. 10. The result indicates the network loss in case of 6PSC conversion is lower than that at 3PDC conversion.

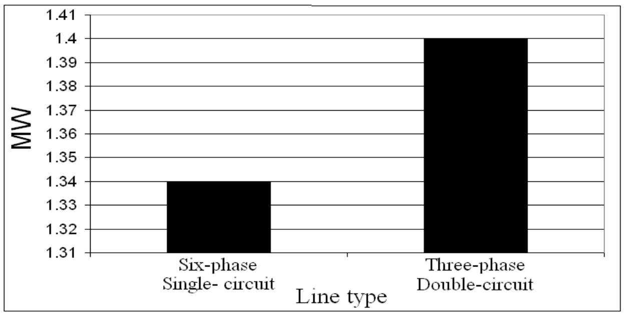


Figure 10. Total loss by converting line 8-9 to a 3PDC and 6PSC line

Finally, for arc furnace load connected at bus 5, RMS and TIF of line currents and RMS and THD of bus voltages are calculated and shown in Tables XIII-XVI. The obtained results with arc furnace load show that in case of 6PSC line conversion, TIF of line currents and THD of bus voltages, except bus 5, are absolutely greater compared to those values calculated for 3PDC line conversion. So, if only one line of the existent network is converted, TIF of currents is greater in 6PSC line than 3PDC conversion. However, the values of THD depend on type of harmonic source.

TABLE XIII.
RMS AND TIF OF LINE CURRENTS (CONVERSION OF LINE 8-9 TO 3PDC LINE), ARC FURNACE LOAD

| Line No. | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 4-9 |
|---|---|---|---|---|---|---|
| RMS Current (A) | 219 | 70 | 83 | 180 | 54 | 220 |
| TIF (%) | 99 | 252 | 199 | 62 | 33 | 92 |

TABLE XIV.
RMS AND THD OF BUS VOLTAGES (CONVERSION OF LINE 8-9 TO 3PDC LINE), ARC FURNACE LOAD

| Bus No. | RMS Voltage (%) | THD (%) |
|---|---|---|
| 1 | 100.18 | 5.94 |
| 2 | 100.27 | 7.37 |
| 3 | 100.15 | 5.55 |
| 4 | 99.57 | 10.79 |
| 5 | 99.52 | 13.25 |
| 6 | 100.16 | 11.31 |
| 7 | 99.52 | 11.95 |
| 8 | 99.75 | 11.41 |
| 9 | 98.92 | 11.43 |

TABLE XV.
RMS AND TIF OF LINE CURRENTS (CONVERSION OF LINE 8-9 TO 6PSC LINE), ARC FURNACE LOAD

| Line No. | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 4-9 |
|---|---|---|---|---|---|---|
| RMS Current (A) | 216 | 87 | 97 | 190 | 31 | 248 |
| TIF (%) | 249 | 374 | 414 | 59 | 281 | 219 |

TABLE XVI.
RMS AND THD OF BUS VOLTAGES (CONVERSION OF LINE 8-9 TO 6PSC LINE), ARC FURNACE LOAD

| Bus No. | RMS Voltage (%) | THD (%) |
|---|---|---|
| 1 | 100.19 | 6.15 |
| 2 | 100.57 | 10.7 |
| 3 | 100.16 | 5.66 |
| 4 | 100 | 11.13 |
| 5 | 99.91 | 13.2 |
| 6 | 100.6 | 11.48 |
| 7 | 100.57 | 14.89 |
| 8 | 101.28 | 16.43 |
| 9 | 100 | 15.02 |

Consequently if harmonics are considered, in case of conversion of one line, 3PDC line conversion is the better alternative for network restructuring. While neglecting harmonics, 6PSC line conversion would be worth.

## VI. CONCLUSIONS

In order to increase the power transfer capability of the existing network to meet the increasing energy demand, conversion of 3PSC to 3PDC line and high phase order transmission line (e.g. 6PSC line) are well known approaches. Usually, constraints maybe used to decide on the optimal alternative, are total loss of the network and desirable voltage limits, while the system harmonics are neglected. However, harmonics can affect on network loss and value of bus voltage and reduce the power quality. Thereby, in order to obtain the accurate result or adopt an optimal alternative for network conversion, harmonics should be considered.

In this paper, harmonic analysis due to conversion of a 3PSC network to 3PDC and 6PSC system is studied. The analysis is performed for conversion of entire network and one line in the network, separately.

The results show that if harmonics are omitted, considering total loss and voltage limits, conversion of existing network to 3PDC network is the better alternative compared to 6PSC network. But if the harmonic indices are used as decision parameters, conversion of the existing network to 6PSC system leads to better situation.

Therefore, in any optimization algorithm in order to achieve more accurate results, the effect of harmonics on power system parameters such as total loss, voltage limits and power quality issues should be considered simultaneously.

Referring to studies performed in this paper, TIF of currents is dependent on the type of conversion and is different for 3PDC and 6PSC system. But THD of voltages completely depends on the type of harmonic source in the network.

Moreover, analysis of the results of frequency scan shows that the number of resonances is more in 6PSC conversion than 3PDC conversion. Also magnitude of high-frequency impedance at 6PSC conversion is greater compared to 3PDC leading to less propagation of disturbances along the system during high-frequency transients disturbances such as lightning surges.

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