Feasibility and Impact of Using Six-Phase Line in a Specific Distribution and Sub-Transmission System

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***Abstract*—Power loss issue is one of the most significant issues encountered in electrical industry and it is essential to note. System design is essentially to ensure that the increased electricity demand could be meeting by power system development, so that it becomes technically a suitable and economical system. Distribution system has a particular importance in electrification due to: 1) near perfectly to the consumers 2) high investment cost. On the other hand, about 67% of power grid loss is related to the distribution system. Beside, conversion of 3-Phase Double-Circuit (3PDC) to 6-Phase Single-Circuit (6PSC) line is known as a well method to increase the power transfer capability of existing ROWs. Thus, in this paper, an investigation of conversion of existing 3-Phase Single-Circuit (3PSC) lines to the 3PDC to 6PSC lines is studied and compared. It is found that with the same transmitted power in the 3PDC and 6PSC states, using the 6PSC line in suitable places of sub-transmission and distribution systems will dramatically result in decreased loss and improved voltage regulation. In all the cases, test power system is assumed as a balanced system.**

Keywords-active power; distribution system; loss; sub-transmission system; voltage; 6PSC; 3PDC

I. INTRODUCTION

Power loss issue is one of the most significant issues encountered in electrical industry and it is essential to note. Generally, the reduced electrical energy loss is that generation, transmission and distribution networks capacity increase without investing on generation option. For example, based on information of interpretive statistics leaflet of Iranian electrical industry, total loss existed in the Iranian transmission and distribution networks (together with internal load of power plants) is given to 20.5% of total generation. This percentage is an average value and peak loss will nearly reach to 30%, so damage imposed to the state electrical industry is very high. Point that should be warned is that more than 67% of loss is occurred in distribution and sub-transmission networks. Thereby, attentions should be inevitably attracted to reduce the loss of these networks.

Beside, nowadays power system voltage is nearly reached to the maximum value itself and voltage increment is nearly impossible. Because, high voltage lines will result in making the highly electromagnetic fields, biological effects, sonic disturbances and also will need to take justification in order to construct the power lines, so finding the suitable alternative methods is included as commitments of distribution division.

Emerging energy crisis and concerning the optimal operation of energy resources and generation- transmission systems have been resulted in making serious researches on high phase order lines (that is 6, 9, 12 … phase lines) [1].

Also based on the researchers' results, among the HPO, six-phase transmission is appeared to be the most promising solution to the need to increase the capability of existing transmission lines [2-7] and at the same time, it responds to the concerns related to electromagnetic fields [6-9].

NYSEG (New York State Energy Electric and Gas Corporation) HPO demonstration project (1982) is a major step forward in promoting this technology and in demonstrating the technical and environmental benefits of HPO transmission [10]. Some of these potential benefits over three-phase system are as well: smaller structure [10], lower insulation requirement [2], better stability margin [7], better voltage regulation [10] and increased power transfer under faulted conditins [11].

A balanced 6-phase system has 60º electrical difference between each phase as shown in Fig. 1.

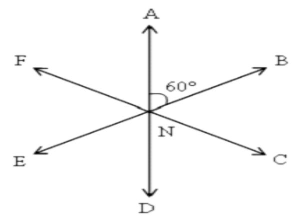

Figure 1. Phasors of a 6-Φ System [12].

Three-phase line can be easily converted to a six-phase line using conversion transformers (Fig. 2), which make the required 60° phase shift at six-phase operation side [12]. So, it is clear that the construction cost of terminals will restrict application of the six-phase lines.

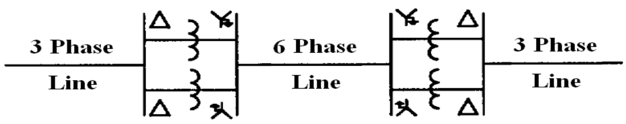

Figure 2. 6PSC line configuration having the conversion transformers.

NYSEG demonstration project shows exact cost values for converted 3PDC to 6PSC line serving to clarify cost values related to the 6PSC lines [9].

In this paper, application of 6PSC system in a 20kV radial distribution and in a 63kV open-loop sub-transmission network is studied. Firstly, after converting each of the existing 3PSC lines to the 3PDC and 6PSC line, load flow analysis is done and then the better conversion location is determined based on minimum active power loss. Afterwards, the most suitable conversion type is chosen. The criteria used in choosing the better conversion type are total network loss and remaining the buses voltage magnitude in the allowable ranges.

In continue, the conversion of the entire 3PSC network to the 3PDC and 6PSC network is analyzed and the most suitable network is determined by using the achieved results.

In fact, comparison between 3PDC and 6PSC systems is the purpose of this study, as the feasibility and impact of using the 6PSC lines become determined to reduce the loss when total loss of network is very high.

To simulate, phase voltage of 6PSC line is increased up to 173% of 3PDC line. Because, as shown in Fig. 1, phase to adjacent phase voltage is 173% higher in 3PDC line to the 6PSC line. So, considering the insulating distance between the phases, the phase voltage of 6PSC lines could be increased to 173%.

II. 20kV Distribution Network

A real 13-buses distribution network located in Tehran, Iran is selected as a case study. Here, the values of 100%, 60% and 10% are considered as peak, average and base loads, respectively. Also, bus #1 is considered as the main bus (swing bus) with 1p.u. voltage level.

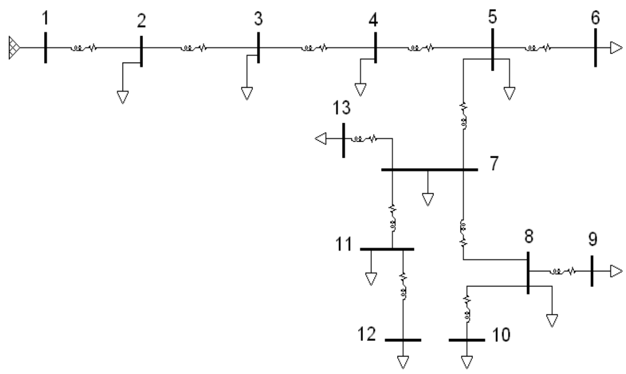

Figure 3. One-line diagram of test radial 20kV distribution network.

A. *Conversion of One of the Existing Lines to the 3PDC and 6PSC Line*

In this section, each of the existing 3PSC lines are separately converted to the 3PDC and 6PSC line, and finally the most suitable conversion location is determined in the average load condition. As mentioned before, the criterion used to select the suitable location is the total active power loss.

Fig. 4 shows the total network loss in the average load condition, when every 3PSC line of above network is separately converted to the 3PDC and 6PSC line.

The results show that in the 3PDC conversion, the least value of active power loss is related to the conversion of line 1-2 and it is 18.6% less than the same 3PSC system; also the highest one is related to the conversion of line 5-6 and it is changed nearly zero than the same 3PSC system.

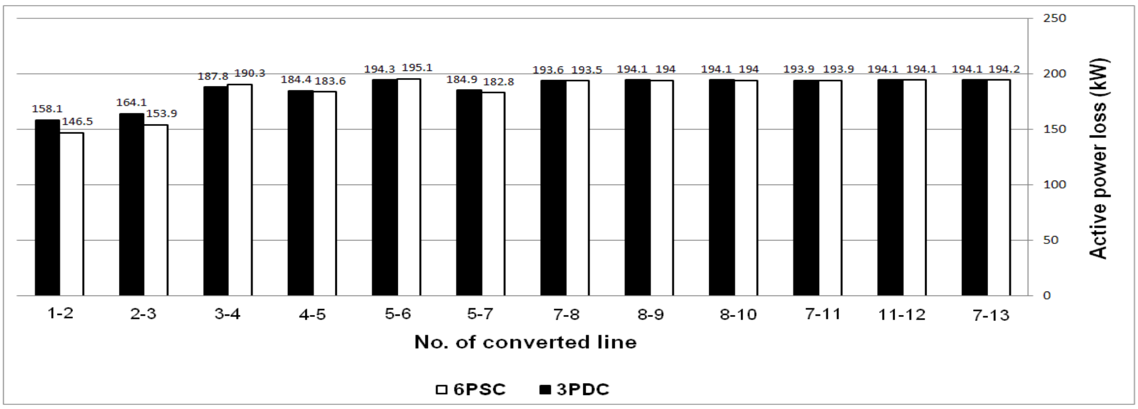

Figure 4. Active power loss of radial distribution network having the converted lines to the 3PDC and 6PSC line in the average load condition.

Further, in the 6PSC conversion the least value of active power loss is related to the conversion of line 1-2, 24.6% less than the same 3PSC system; and the conversion of line 5-6 not only does not result in decreasing loss, but also increase the loss up to 0.4% compared to the same 3PSC system.

Therefore, the conversion of 3PSC lines included much loss, usually these lines are located at the first of the radial distribution network, to the 3PDC and 6PSC line results in sensibly decreasing the power loss that this loss is more decreased when the 6PSC conversion is applied as compared to the 3PDC conversion. However, applying the 6PSC system is a function of the applied location, as in conversion of some lines to the 6PSC type the loss reduction is more salient than the 3PDC type, but in conversion of other lines the loss is not sensibly changed and even is increased.

Fig. 5 shows the voltage magnitude of busses in the average load condition when only 3PSC line 1-2 is converted to the 3PDC and 6PSC line. The following results show that if the existing line is converted to the 3PDC and 6PSC line, then the voltage magnitude of busses is remained in the standard range (95%- 105% of nominal voltage). In the 3PDC system, compared to the 3PSC system i.e. the busses voltage magnitude of 3PSC system is considered as a base, the highest value of increased voltage is 1.16% related to the busses #9 and #10 and the least value of increased voltage is 0.37% related to the bus #2; and also in the 6PSC system, the voltage magnitude of all the busses is lied in the allowable range and it is reduced up to the maximum 1.3%. This issue is resulting from the increased reactive power loss due to the used conversion transformers resulting in the reduced power factor of the network.

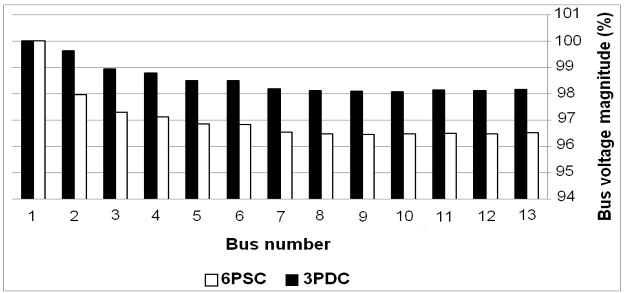

Figure 5. The busses voltage magnitude in the average load condition, when only line 1-2 is converted to the 3PDC and 6PSC line.

Now, the effect of 3PDC and 6PSC lines is being studied on network loss and busses voltage magnitude in the base and peak load conditions. The results of the load flow are shown in Fig. 6 for the base load condition. The results show that the active power loss of the 3PDC system is 4.4kW reduced up to 21.4% as compared to the 3PSC system. Also, the active power loss of the 6PSC system is 4.2kW reduced up to 25% as compared to the 3PSC system.

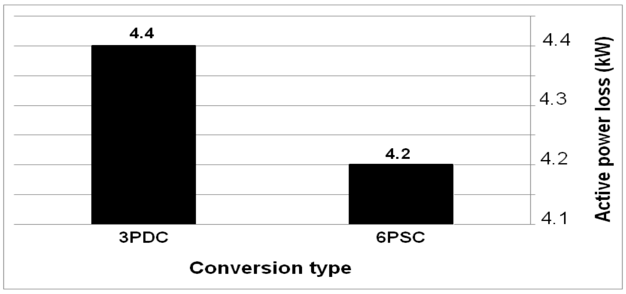

Figure 6. The active power loss in the base load condition, when only line 1-2 is converted to the 3PDC and 6PSC line.

Also, the results show that the busses voltage magnitude of both systems is lied in the standard range, for the base load condition.

Further, the analyses are done in the peak load condition. In this condition, the voltage magnitude of some busses is less than the allowable limit, so the voltage magnitude of busses is changed up to the maximum 1% to lie in the allowable range by changing the tap-changer of the four conversion transformers. The active power loss is shown in Fig. 7 for the peak load condition. The results show that the active power loss of 3PDC system is 443.7kW reduced up to 18.7% as compared to the same 3PSC system. Also, the active power loss of 6PSC system is 422.5kW reduced up to 22.6% as compared to the same 3PSC system.

So, the line 1-2 is suitable location in order to the conversion of the 3PSC or 3PDC line to the 6PSC line. This selected line is due to minimum active power loss and the voltage magnitude of busses remained in the allowable range, in all the load conditions, when the existing line is converted to the 6PSC line.

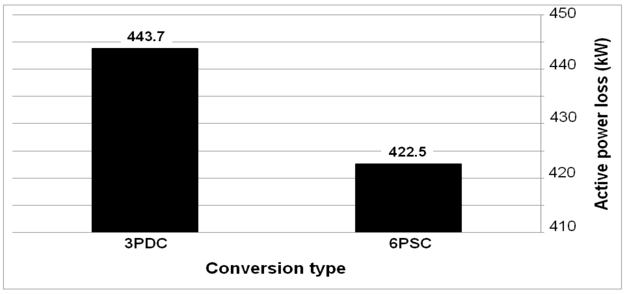

Figure 7. The active power loss in the peak load condition, when only line 1-2 is converted to the 3PDC and 6PSC line.

B. Conversion of the Entire Network to the 3PDC and 6PSC Network

In this section, all the lines are converted to the 3PDC and 6PSC line. Fig. 8 shows the voltage magnitude of busses when the above network is converted to the 6PSC network in the average load condition. As the results show, the voltage magnitude of busses is not lied in the allowable range (95%-105% of nominal voltage); this issue is because of increased reactive power loss due to applying many number of conversion transformers located in the every line.

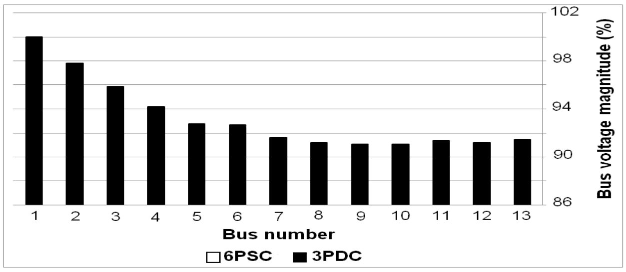

Figure 8. The busses voltage magnitude of the 6PSC network in the average load condition.

To compensate the much voltage drop of some busses of 6PSC network, different methods could be used; such as using the capacitive compensators, changing the tap-changer of some transformers, using high nominal capacity transformers and etc. But since increasing the number of conversion transformers results in increased the reactive power loss and accordingly increased the reactive power demand, so the capacitive compensators are chosen to compensate the reactive power and improve the power factor.

The total active power loss of 6PSC and 3PDC network (when the capacitive compensators are used in both networks) for the average load condition is shown in Fig. 9. The active power loss of the same 3PSC network is considered as a base value. The results of Fig. 9 show that the active power loss of 3PDC and 6PSC network is reduced up to 58% and 59.1%, respectively. Considering the active power loss of 6PSC network that is less than 3PDC network, but increased voltage drop of busses, reduced power factor and also need to the high economic budget to provide the conversion transformers, it is concluded that the 6PSC network is not advantageous than the 3PDC network. This voltage drop is even worse in the peak load condition; therefore, the results are not shown for the peak and base load conditions.

III. 63kV Open-Loop Sub-Transmission Network

In this section, a test sub-transmission network, as shown in Fig. 10, is selected (bus #1 is considered as the swing bus with V=1p.u.). Also in this section, analyses are done only for the base load condition.

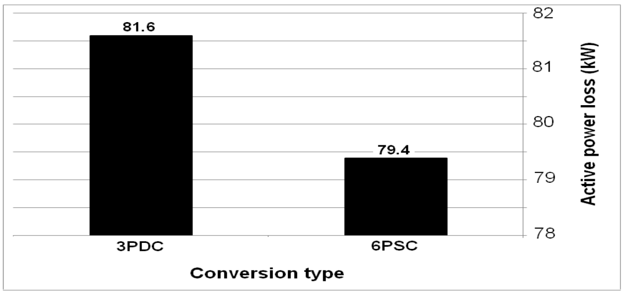

Figure 9. The active power loss of the 3PDC and 6PSC networks in the average load condition.

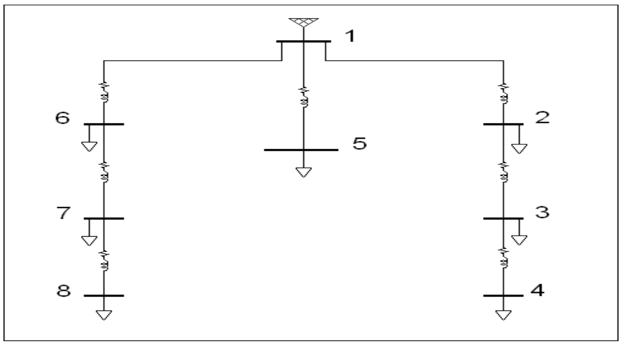

Figure 10. One-line diagram of test 63kV sub-transmission network.

A. Conversion of One of the Existing Lines to the 3PDC and 6PSC Line

In this section, each of the 3PSC existing lines is separately converted to the 3PDC and 6PSC line and finally the most suitable conversion location is selected.

Fig. 11 shows the network loss when each of the existing lines is converted to the 3PDC and 6PSC line in the average load condition. The results show that in the 3PDC system, the least value of the active power loss is 1189.4kW related to the conversion of line 6-7 (reduced up to 10.7% than the 3PSC state), and the highest value of the active power loss is 1284.5kW related to the conversion of line 3-4 (reduced up to 3.6% than the 3PSC state).

Also, in the 6PSC system, the least value of the active power loss is 1102.9kW related to the conversion of line 6-7 (reduced up to 17.2% than the 3PSC network), and the highest value of the active power loss is 1255.7kW related to the conversion of line 3-4 (reduced up to 5.7% than the 3PSC network).

Also, the results show that the effect of 3PSC line conversion to the 6PSC and 3PDC line on reducing the loss is dependent on the active power loss of the existing line, as the more the active power loss of line, the more the effect of its conversion to the 6PSC and 3PDC line on reducing the total network loss. Also, in the studied 63kV network unlike the 20kV network, using the 6PSC system results in reducing more active power loss than the 3PDC system.

Fig. 12 shows the voltage magnitude of the busses when only line 6-7 is converted to the 3PDC or 6PSC line. The results show that the voltage magnitude of the busses is remained in the standard range (95%- 105% of nominal voltage) when the existing 3PSC line is converted to the 3PDC or 6PSC line. In the 3PDC system, as compared to the 3PSC system, the highest value of increased voltage is 0.22% related to the bus #8 and the least value of increased voltage is nearly zero related to the adjacent feeders; also in the 6PSC system the highest value of increased voltage is 1.25% related to the bus #8 and the least value of increased voltage is nearly zero related to the adjacent feeders. So, based on the achieved results, the application of 3PDC and 6PSC lines in a feeder has not any effect on power loss and busses voltage of other feeders and also unlike the 20kV distribution network, using the 6PSC line results in increasing the busses voltage in same feeder.

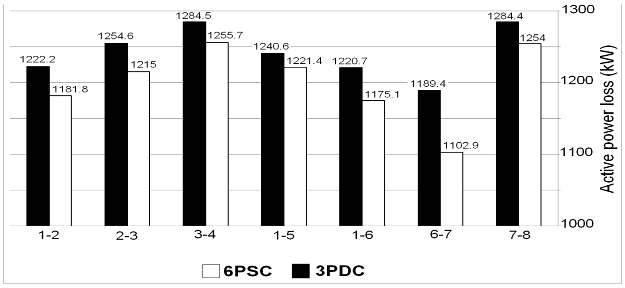

Figure 11. The active power loss of the sub-transmission network in the average load condition, when the 3PDC and 6PSC conversions are applied in each line.

Therefore, the most suitable conversion location is line 6-7. This selection is due to minimum active power loss and remaining the voltage magnitude of busses in the allowable range.

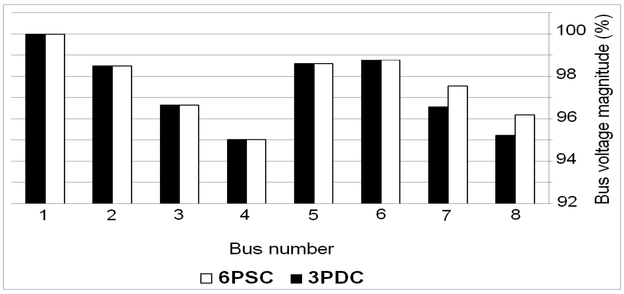

Figure 12. The busses voltage magnitude in the average load condition, when only line 6-7 is converted to the 3PDC and 6PSC line.

B. Conversion of the Entire Network to the 3PDC and 6PSC Network

In this section, all the existing lines are converted to the 3PDC and 6PSC line. Fig. 13 shows the voltage magnitude of busses when the entire network is converted to the 3PDC and 6PSC network.

As the results show, the voltage magnitude of the busses is not remained in the standard range (95%- 105% of nominal voltage). This fact is due to increased reactive power loss because of many conversion transformers used in every line. Also, Fig. 14 shows the networks loss and it is clear that the 6PSC network has less active power loss than the 3PDC network.

Here, since increase of the number of conversion transformers results in increasing the reactive power loss and accordingly the reactive power demand of the network, the capacitive compensators are used to compensate much voltage drop of some busses and also improve the network power factor.

The load flow results of 6PSC and 3PDC networks are shown in Figs. 15 and 16, when the capacitive compensators are used. The results show that the active power loss of 3PDC network is 624kW, reduced up to 53.15% than the same 3PSC network; and the active power loss of 6PSC network is 379.4kW, reduced up to 71.5% than the same 3PSC network.

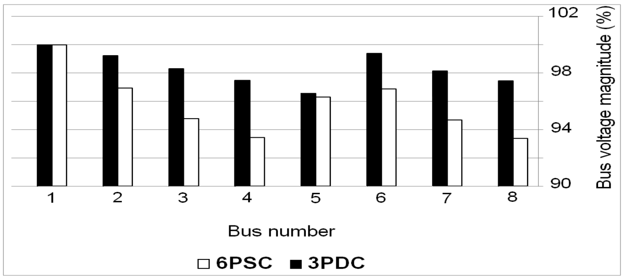

Figure 13. The busses voltage magnitude in the average load condition, when the entire sub-transmission network is converted to the 3PDC and 6PSC networks.

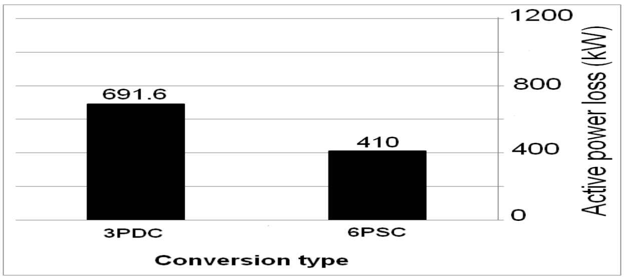

Figure 14. The active power loss in the average load condition, when the entire sub-transmission network converted to the 3PDC and 6PSC networks.

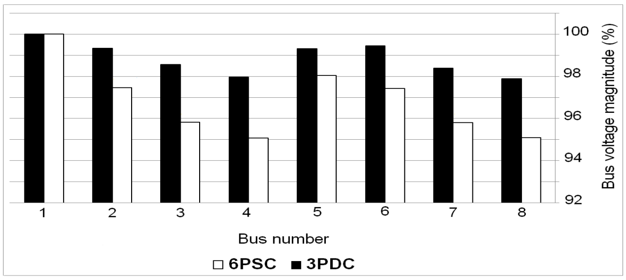

Figure 15. The busses voltage magnitude in the average load condition, when the entire network is converted to the 3PDC and 6PSC networks and the capacitive compensators are used.

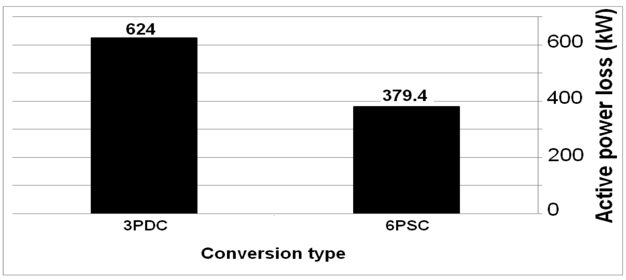

Figure 16. The active power loss in the average load condition, when the entire sub-transmission network is converted to the 3PDC and 6PSC networks and the capacitive compensators are used.

IV. CONCLUSION

The results show that the conversion of the existing 3PSC line to the 6PSC line results in providing some advantages and disadvantages as compared to the 3PDC conversion. They are concisely:

- The conversion of lossy lines, usually these lines are located in the first of radial distribution network, to the 6PSC line results in sensible reduction of active power loss.
- Therefore, using the 6PSC line could postpone the construction of new distribution lines or increase the network efficiency by transmitting more power.
- If the 6PSC line is used, then the voltage drop of the radial distribution network could be more than the 3PDC system due to the high reactive power consumed by the conversion transformers.
- The active power loss of the 6PSC distribution network is some reduced than the 3PDC network. But, because of the increased voltage drop of busses, reduced network power factor and need to the much economic budget to provide the conversion transformers, it could be mentioned that the radial 6PSC distribution network is not advantageous than the 3PDC network. This voltage drop is even worse in the peak load condition.
- In the open-loop sub-transmission network, applying the 6PSC line in the most lines results in increased busses voltage and reduced network loss.
- In the open-loop sub-transmission network, if the entire network is converted to the 6PSC network, then the busses voltage would not be in the allowable range resulting from increased reactive power loss of network because of applying many conversion transformers located in every lines. However, the active power loss of the 6PSC network is more reduced than the 3PDC network.

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