Disturbance Analysis in Conversion of Double Three-Phase to Six-Phase Transmission Network

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***Abstract*—Fault occurrence in power systems could result in losing their stability and cause severe damages in faulted devices or adjacent healthy devices. Also, stability proposition is charged as an important component in energy management and planning of power systems. Moreover, during the motor starting period, it draws a large current from the system, results in voltage drop of system and poses disturbances to the normal operation of other loads. Hence, fault and induction motor starting analysis are important studies in design and development of power systems. Beside, conversion of 3-phase double-circuit (3PDC) to 6-phase single-circuit (6PSC) line is a well known method to increase the power transfer capability of the network. So in this paper, an investigation of fault occurrence and motor starting for 3PDC converted to 6PSC transmission line is studied. According to the achieved results, if network is converted to 6PSC network, then system performance from view of transient stability and motor starting could improve, but magnitude of fault current may be increased than the 3PDC network. In this study, power system is assumed as a balanced system. Other economical and practical factors can be studied for planning, development and design of future transmission networks.**

I. INTRODUCTION

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. But 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 (6, 12 and more phases), was conceived as a means for increasing the power transfer capability of existing ROW space [1].

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 it responds to the concerns related to electromagnetic fields [6]-[9].

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 operation side [10].

NYSEG (New York State Energy Electric and Gas Corporation) HPO demonstration project is a major step forward in promoting this technology and in demonstrating the technical and environmental benefits of HPO transmission [11]. Some of these potential benefits over three-phase systems are as well: smaller structure [11], lower insulation requirement [2], better stability margin [7], better voltage regulation [10]-[11] and increased power transfer under faulted conditins [12].

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

A review of the literature reveals that 6PSC line often was considered as a compact line shown in Fig. 2. But the most applicable and simplest scheme can be conversion of an existing 3PDC to 6PSC transmission line at the same structure.

One of the most important items in applying multi-phase alternative in transmission planning is the design of an adequate protective scheme. This requires a detailed and realistic fault analysis. General definition for fault is “any failure that interferes with the normal flow of current”. Also, dynamic performance of a power system is significant in its design and operation.

Moreover, during the motor starting period, motor is appeared to the system as small impedance connected to a bus. Thereby a large current is drawn from the system, about six times the motor rated current, and therefore voltage drop is occurred in the system.

So in this paper, the analysis of fault and motor starting in application of 3PDC and 6PSC lines are studied. Conversion of either the entire network or one of the existing lines to 3PDC and 6PSC is studied.

II. FAULT ANALYSIS

The fault analysis in six-phase power systems are more complicated than in the conventional three-phase power systems. This is due to the fact that there are six-phases, each subjected to a different voltage, and the presence of a neutral makes the number of fault types much greater. The total number of possible faults in three-phase system is 11; while that in six-phase system is 120. Also, the number of possible significant faults in three-phase and six-phase systems is 5 and 23, respectively [10], [13].

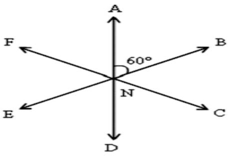

Figure 1. Phasors of a 6-Φ System [10]

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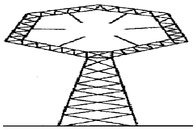

Figure 2. Six-phase compact structure [4]

In six-phase systems, six-phase faults are the least common while single-phase-to-ground faults are the most common. In addition, faults involving two and three phases with several distinct possibilities could be more frequent in six-phase systems compared to three-phase systems [10].

III. POWER SYSTEM STABILITY

Power system stability is a measure of the inherent ability of the system to recover from extraneous disturbances (such as faults, lightings or changes of load), as well as from planned disturbances (such as switching operations) [14].

It is common to find out stability issue as one issue to maintain synchronism of generators, but it is possible to be unstable without losing the synchronism. For instance, in a system having induction motor load, it is possible to be unstable due to voltage collapse. The maintenance of synchronism is not introduced in this state; rather voltage stability is significant.

A. Rotor angle stability

Rotor angle stability is referred as the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. Large disturbance rotor angle stability or transient stability is the most known type of this stability, connected with the ability of the power system to maintain synchronism when it is subjected to a severe disturbance, such as a short circuit on a transmission line [14].

The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship [10].

Fig. 3 illustrates the behavior of a synchronous machine for stable and unstable situations. In case 1 (stable case), the rotor angle increases to a maximum, then decreases and oscillates with decreasing amplitude until reaches a steady-state.

In case 2, the rotor angle continues to increase steadily until synchronism is lost. This form of instability is referred to as first-swing instability and is caused by insufficient synchronizing torque. In case 3, the system is stable in the first-swing but becomes unstable as a results of growing oscillations as the end state is approached. This form of instability generally occurs when the post-fault steady-state condition itself is “small-signal” unstable, and not necessarily as a result of the transient disturbance [10].

The time frame of interest in transient stability is usually 3 to 5*s* following the disturbance. It may extend to 10-20*s* for very large systems.

B. Voltage Stability

Voltage stability is becoming an increasing source of concern in secure operation of present-day power systems. A power system at a given operating state and subject to a given disturbance is “voltage stable” if voltages near loads approach post-disturbance equilibrium values. Voltage instability is the absence of voltage stability, and often results in progressive voltage decrease [15].

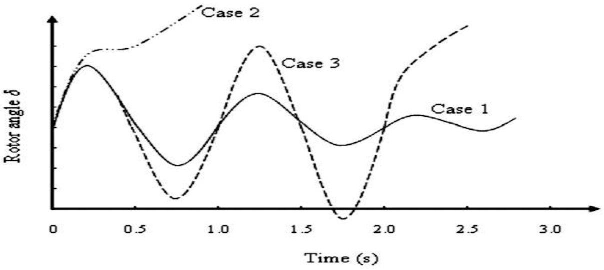

Figure 3. Rotor angle response to a transient disturbance [10]

Note, the rotor angle stability is seldom a reason for the restriction of power transfers due to stronger power systems and development of equipment technology compared to past decades, while the power system blackouts occurring all over the world have in the past years mainly been voltage collapses. Voltage collapse is the catastrophic result of a sequence of events leading to a low-voltage profile suddenly in a major part of the power system [16].

IV. CASE STUDY

The case study diagram is shown in Fig. 4. This network consists of 3 generators, 3 transformers, 3 loads, 6 transmission lines and totally 9 buses as shown in Fig. 4.

There are five common combinations that can be used to form a three to six-phase conversion transformer which are Y-Y & Y-Y inverted, Δ-Y & Δ-Y inverted, diametrical, double-delta and double-Y [10]. In this paper, the Δ-Y & Δ-Y inverted connection was selected as shown in Fig. 5. Because the delta open circuits the zero sequence network and simplifies the fault analysis [10]. One of each pair of transformer has reverse polarity to obtain the required 60° phase shift.

As for in a six-phase system, the magnitude of phase-to-phase voltage is equal to the magnitude of the phase-to-neutral voltage, so the phase voltage of six-phase side was increased up to √3 times of the three-phase side.

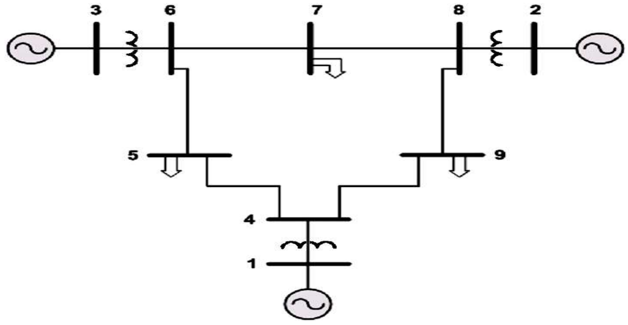

Figure 4. Case study diagram

V. CONVERSION OF THE ENTIRE NETWORK

In this section, all existing lines of test system were converted to 6PSC & 3PDC lines.

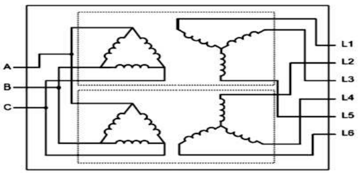

Figure 5. Schematic diagram of "Δ-Y and Δ- Y Inverted" connected three-to-six-phase conversion transformer [10], [12]

A. Fault Analysis

The main purpose of the fault study is to determine the magnitude of fault current for various types of fault [17]-[18]. In this study, standard IEC 909 is used.

For different types of short-circuit in *kth* bus, the following relations for sequence-currents can be established:

Single phase to ground fault:

$$I_k^0 = I_k^+ = I_k^- = \frac{V_k(0)}{Z_{kk}^0 + Z_{kk}^+ + Z_{kk}^- + 3Z_f} \tag{1}$$

Two phase fault:

$$I_k^+ = -I_k^- = \frac{V_k(0)}{Z_{kk}^+ + Z_{kk}^- + Z_f} \quad \text{و} \quad I_k^0 = 0 \tag{2}$$

Two phase to ground fault:

$$I_k^+ = \frac{V_k(0)}{Z_{kk}^+ + \dfrac{Z_{kk}^-\left(Z_{kk}^0 + 3Z_f\right)}{Z_{kk}^- + Z_{kk}^+ + 3Z_f}}, \quad I_k^- = -\frac{V_k(0) - Z_{kk}^+ I_k^+}{Z_{kk}^-}$$

$$I_k^0 = -\frac{V_k(0) - Z_{kk}^+ I_k^+}{Z_{kk}^0 + 3Z_f} \tag{3}$$

Three phase fault:

$$I_k^+ = \frac{V_k(0)}{Z_{kk}^+ + Z_f} \quad \text{و} \quad I_k^0 = I_k^- = 0 \tag{4}$$

Where, $V_k(0)$ is the magnitude of bus voltage when fault is occurred and Z_f is fault impedance. In this study, short-circuit fault was applied at buses#5, 7 and 9 and Z_f was assumed zero. Because most of short circuit faults occurred in transmission network has zero fault impedance. Detailed results of fault analysis for 3PDC and 6PSC cases are tabulated in Table I.

As positive, negative and zero sequence currents are the same in single-phase to ground faults, and as zero sequence current cannot be flowed out of delta connected transformer terminals, so for 6PSC conversion, current magnitude of single-phase to ground fault in load buses is zero.

Also as in 6PSC network, bus voltages are increased, due to increase of capacitive effect of lines, and sequence impedances seen at buses are decreased than 3PDC network (Table II), so the fault current is increased in 6PSC compared to 3PDC network.

B. Stability Analysis

The stability analysis has been conducted to the test system for both 3PDC and 6PSC transmission networks. Fault was occurred at bus#5 at 1 second and cleared at 1.5 second. Fig. 6 illustrates the changed rotor angle of generator#3 for the given condition.

TABLE I. THE MAGNITUDE OF FAULTS CURRENT IN 6PSC AND 3PDC NETWORK, PER RMS-KA

Faulted bus no.	**Conversion type**	**Single phase to Ground**	**Two phase**	**Two phase to Ground**	**Three phase**
Bus 5	3PDC	10.92	12.57	13.39	11.94
	6PSC	00.00	16.87	16.87	17.63
Bus 7	3PDC	12.99	14.33	15.32	13.89
	6PSC	00.00	18.09	18.09	18.97
Bus 9	3PDC	11.44	13.24	14.05	12.34
	6PSC	00.00	17.50	17.50	17.92

TABLE II. THE MAGNITUDE OF SEQUENCE IMPEDANCES SEEN AT LOAD BUSES

Bus no.	**Conversion type**	**Positive-negative sequence impedances (Ω)**	**Zero sequence impedances (Ω)**
Bus 5	3PDC	10.07	20.00
	6PSC	7.50	00.00
Bus 7	3PDC	8.83	16.07
	6PSC	6.99	00.00
Bus 9	3PDC	9.56	19.19
	6PSC	7.23	00.00

It is found that the rotor angle will swing when a fault is applied to the test system and after fault is cleared, it will reach the stable region. However, unlike the 6PSC network at the 3PDC network the rotor angle finally reaches a stable region except the pre-fault region.

Also, Fig. 7 illustrates the changed voltage of bus#7 for the given condition. It is found that the variation of buses voltage due to fault occurrence is decreased in 6PSC than 3PDC network.

Totally, stability performances of the 6PSC network are better as compares to 3PDC network. Since to cause the instability, the 6PSC network requires longer time of disturbances occurrence, in other words the stability of the 6PSC network is increased.

C. Analysis of Induction Motor Starting

To analyze, an induction motor 60MVA was started at bus#5. Starting current and voltage drop of motor bus are observable in Figs. 8- 9 for both 6PSC and 3PDC networks.

The results above show that motor starting current in 6PSC network is insensibly increased, but voltage drop at motor bus is dramatically less than 3PDC network. This circumstance is due to increased active and reactive power transfer to induction motor started at 6PSC network compared to 3PDC network.

VI. CONVERSION OF ONE LINE

In previous section, the entire of existing network was converted to a 3PDC and 6PSC network. However, in any optimization algorithm all the possible alternatives must be considered. Maybe conversion of one or some transmission lines instead of entire network leads to better results.

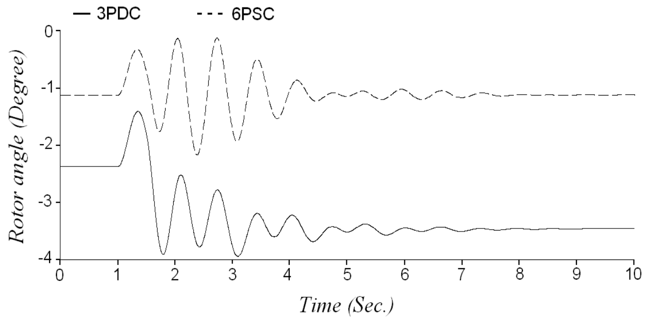

Figure 6. Rotor angle of generator#3 when bus#5 is faulted

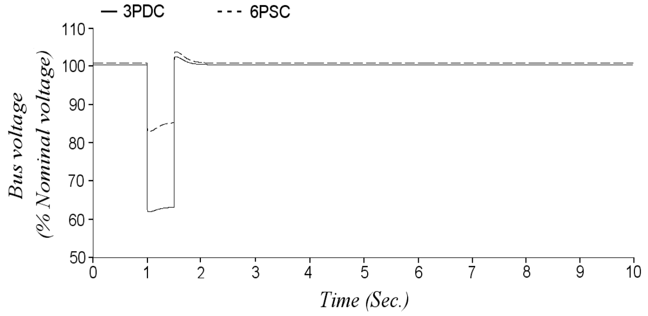

Figure 7. Voltage of bus#7 when bus#5 is faulted

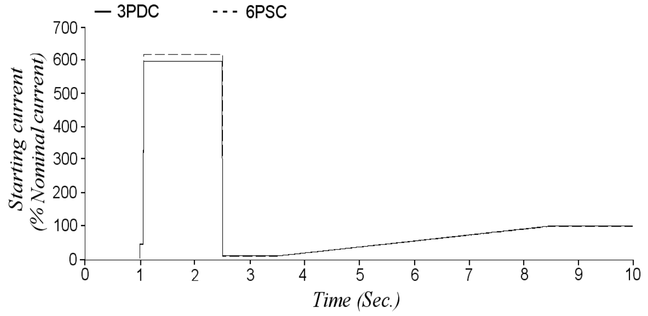

Figure 8. Induction motor starting current

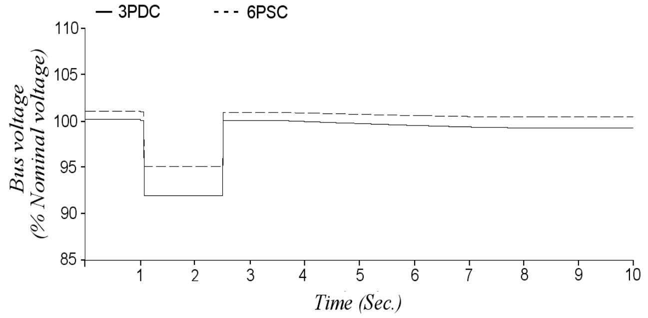

Figure 9. Induction motor terminal voltage

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. Simulation results show that conversion of line 8-9 (line between buses 8 and 9) is the best option for both 3PDC and 6PSC line conversions.

A. Fault Analysis

In this study, short-circuit fault was applied at buses#5, 7 and 9 and Z_f was assumed zero. Detailed results of fault analysis for 3PDC and 6PSC cases are shown in Table III.

According to the Table above, the fault currents are not sensibly changed in 6PSC system compared to 3PDC system. This circumstance is due to nearly equalizing sequence impedances in both configurations (Table IV); though zero sequence impedances of both configurations are sensibly different, but considering aforementioned equations, these impedances have negligible effects on fault currents of two-phases and three-phases short circuits.

B. Stability Analysis

Similar to the previous section, fault is applied to test system (with 3PDC or 6PSC line) at bus#5 at second 1 and cleared at second 1.5. Fig. 10 illustrates the changed rotor angle of generator#3 for the given condition.

TABLE III. THE MAGNITUDE OF FAULT CURRENT IN 8-9 LINE TO 6PSC AND 3PDC LINE, PER RMS-KA

Faulted bus no.	Conversion type	Single phase to Ground	Two phase	Two phase to Ground	Three phase
Bus 5	3PDC	6.99	8.68	9.13	7.98
	6PSC	6.91	8.68	9.12	7.99
Bus 7	3PDC	8.83	10.52	11.09	9.84
	6PSC	8.71	10.53	11.08	9.85
Bus 9	3PDC	10.00	9.09	10.99	11.60
	6PSC	10.13	8.95	11.12	11.31

TABLE IV. THE MAGNITUDE OF SEQUENCE IMPEDANCES SEEN AT LOAD BUSES

Bus no.	Conversion type	Positive-negative sequence impedances (Ω)	Zero sequence impedances (Ω)
Bus 5	3PDC	14.58	33.53
	6PSC	14.57	34.23
Bus 7	3PDC	12.03	25.58
	6PSC	12.01	26.27
Bus 9	3PDC	11.51	25.20
	6PSC	11.38	50.84

It is found out that the rotor angle will swing when a fault is applied to the test system and after fault is cleared, it will reach the stable region. However, unlike the 6PSC system, the rotor angle at the 3PDC system finally reaches a stable region except the pre-fault region.

Also, Fig. 11 illustrates the changed voltage of bus#7 for the given condition. It is found out that the variation of buses voltage is nearly the same for 3PDC and 6PSC systems.

C. Analysis of Induction Motor Starting

To analyze, again an induction motor 60MVA was started at bus#5. Starting current and voltage drop of motor bus are shown in Figs. 12 and 13 for both 6PSC and 3PDC networks.

According to the results above, motor starting current and bus voltage drop are nearly similar in both 3PDC and 6PSC systems. So, it is found out that unlike conversion of entire network, conversion of one of the existing lines to 6PSC line will not sensibly improve the fault current and motor staring current compared to 3PDC conversion. But rotor angle stability is improved than 3PDC network.

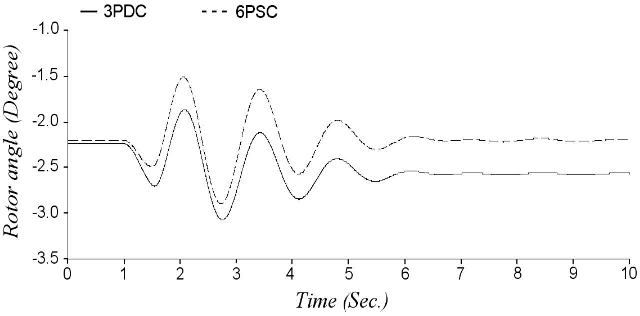

Figure 10. Rotor angle of generator#3 when bus#5 is faulted

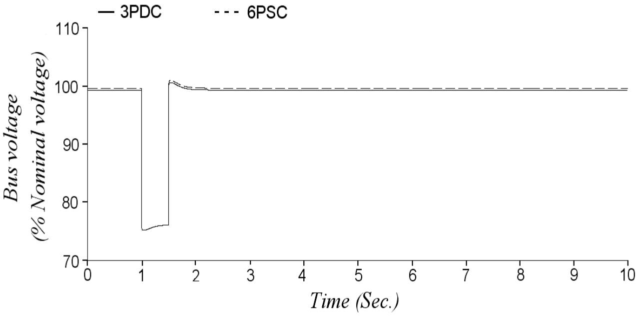

Figure 11. Voltage of bus#7 when bus#5 is faulted

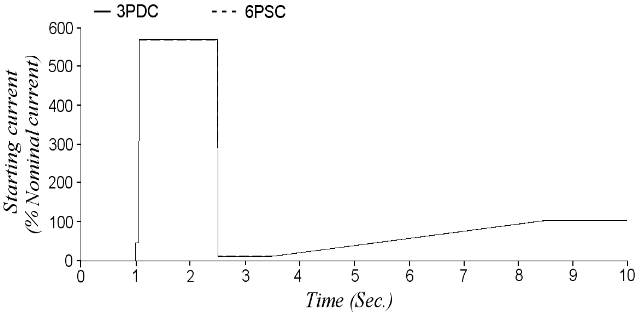

Figure 12. Induction motor starting current

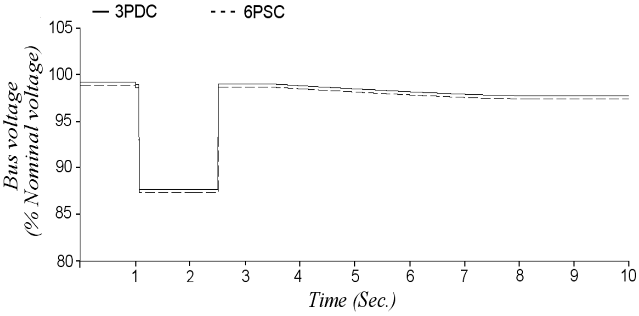

Figure 13. Induction motor terminal voltage

VII. CONCLUSION

In this paper, the analysis of fault current, stability and induction motor starting were studied in both 6PSC and 3PDC conversions known as viable alternatives to increase the power transfer capability.

According to the results, the current magnitude of the fault is increased and voltage drop of existing buses at the moment of starting is decreased in conversion of entire network to 6PSC than 3PDC state.

Also, conversion of one of the existing lines to 3PDC and 6PSC line was studied and it was shown that conversion of one existing line to 6PSC line will not cause sensible changes in the faults current, motor starting current and voltages drop compared to the 3PDC conversion.

Beside, in conversion of either one existing line or entire network to 6PSC state, stability issues (i.e. rotor angle and voltage stability) could improve compared to the 3PDC network.

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