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Stability Analysis of Simultaneous AC-DC Power Transmission System

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***Abstract*- In high voltage long transmission line the power flow is much lower than its thermal limit due to the constraints related to stability and corona discharge. However, in case of simultaneous AC-DC transmission system the power flow can be very close to its thermal limit. Simultaneous AC-DC power transmission system generally increases the load carrying capability and stability of an existing long AC transmission line. The model has two independent components; one represents the loadability feature and other represents the stability feature. The loadability model is based on the development of the correlation between the total power flow of simultaneous AC-DC system and that of pure AC system. The stability model is based on the equal area criterion principle. The model includes the SVPWM controller to generate PWM load line voltage which is equal to given load line voltage. Basically, the stability model is developed considering the three phase to ground fault at the sending end bus. The validation of the model is executed through two different approaches; comparison of the results obtained applying the proposed model to the power system with the published ones in the literature and with the results obtained using standard software, MATLAB simulink, based circuit simulations.**

Keywords: Simultaneous AC-DC transmission system, critical clearing angle, critical clearing time, stability improvement, equal area criterion.

1. INTRODUCTION

Transmission lines are essentially required to transfer electricity from the generation sector to distribution sector. Long transmission lines are designed to transmit electrical energy considering economic factors, network safety and redundancy. Transmission efficiency is improved by maintaining higher and steady voltage level so that lower amount of current is required to transmit desired amount of power. The lower magnitude of current flowing through the line reduces the losses in the conductor and in turn, the receiving end power is nearly equal to the sending end power. Alternating current is very common for the industrial and domestic uses, but AC transmission system has some limitations. The main limiting factor of AC transmission line is the line reactance that limits the power transmitting capacity of the line and stability of the system. Moreover, there are some other problems in AC system such as switching surge causing severe transient over voltage, high degree of corona loss, voltage rise at the receiving end due to Ferranti effect, radio interference in communication system and higher resistance due to skin effect.

The electricity demand is increasing all over the world and to meet this growing demand new plant capacities are added to the system. New remote resources are explored and harnessed for electricity generation to serve the increasing demand. Now, it is a big challenge to transfer vast amount of power from the remote place to the load centre. Construction of new transmission lines may be a solution to mitigate the power transmission crisis but it is a difficult task. To develop the whole structure of new transmission line, a huge investment is required for the acquisition of right-of-way and for the installation of substations, towers and conductors. Besides this, environmental concern and in some cases governmental restrictions put further barriers for delaying the project accomplishment. The effective and quickest solution to solve the power transmission problem is the upgradation of transmission capacity of existing transmission lines. To increase the transmission capacity of a long AC transmission line series and shunt compensation are commonly used. The main disadvantage of series compensation is sub synchronous resonance (SSR) which is close to the natural frequencies of mechanical oscillations of power generating equipment. This SSR may cause the mechanical failure and loss of synchronism of generating unit. Flexible AC transmission systems (FACTS) such as TCSC, TSSC, SSSC are widely used to increase the load carrying capability and stability of existing long EHV transmission system and it reduces the risk of SSR to some extent.

Another novel approach to increase the loadability and stability of an existing transmission system is the simultaneous AC-DC power transmission. In this system DC and AC current flow through the same line and it derives the benefits of parallel HVDC line without constructing the separate DC line. Multilevel inverters generate sinusoidal voltages from discrete voltage levels, and pulse width modulation (PWM) strategies accomplish this task of generating sinusoids of variable voltage and frequency. The SVPWM is considered as a better technique of PWM implementation as it has advantages over SPWM in terms of good utilization of dc bus voltage, reduced switching frequency, low current ripple, better fundamental output voltage and Useful in improving harmonic performance and reducing THD.

2. PROPOSED MODEL

This section presents a mathematical model of a simultaneous AC-DC transmission system. This system of transmission converts an existing AC transmission system to transmit both AC and DC power simultaneously through the same line. The model incorporates neither the conversion process, from AC to DC or DC to AC, nor the control strategies to avoid the complexity in the model. Note that the objective of the study is to develop an appropriate mathematical model to evaluate the improvement of loadability and stability of a transmission line, if it is used to transmit both AC and DC simultaneously compared to the conventional AC line. The loadability issue is considered from [19]. The evaluation of the proposed model presented in this paper provides stability indices. The model development process considers first an AC transmission system, shown in Fig. 1. The system transmits power from a single generator to an infinite bus through a long transmission line. The AC power flow through the transmission line may be expressed as

$$P_l = \frac{E_g E_r}{X_{gr}} \sin \delta_0$$

Xgr = Xte + Xtr

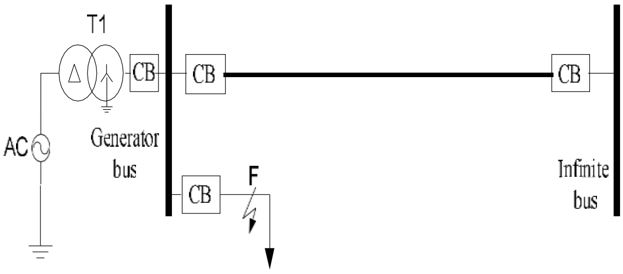


Fig. 1. AC power transmission system

An AC Power transmission system with a fault at the sending end busbar is shown in Figure 1
and its power angle curve is presented in Figure 2. For the proposed long AC transmission line minimum steady state stability margin is recommended as 30-35% and steady state power transfer angle from generator to infinite bus would be 40^{0-} 44^{0} [1]. If a solid 3-phase to ground fault occurs at point F in Figure 1, the power flow through the transmission line will be zero. The power flow through the transmission line can be resumed by isolating the faulted line and the isolation can be performed by tripping the circuit breaker within the faulted line.

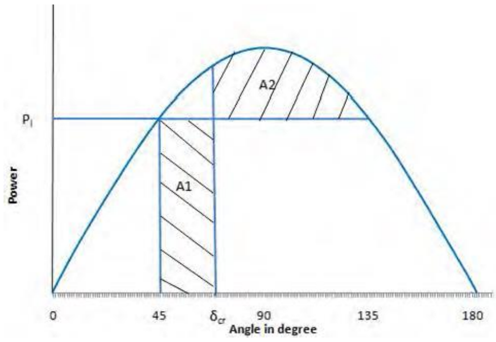


Fig.2 power angle curve

For this kind of fault, according to the equal area criterion of transient stability analysis the accelerating area A1 must be equal to decelerating area A2 as shown in Figure 2. The expression of critical clearing angle and critical clearing time for this transient fault are presented in below Equations.

$$\partial_{cr} = \cos^{-1}[(\pi - 2\partial_0) \sin \partial_0 - \cos \partial_0]$$

$$T_{cr} = \lambda_{ac} \sqrt{\frac{4H}{W_s P_l}}$$

Where, $\lambda_{ac} = \sqrt{\delta_{cr} - \delta_0}$

Simultaneous AC-DC power transmission system

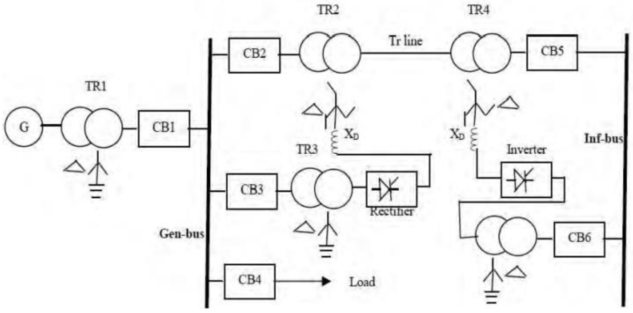


Fig.2.Simultaneous AC-DC Power transmission system

The converted AC system of Fig. 1 into a simultaneous ACDC system is illustrated in Fig. 2. In this system a portion of AC power is converted to DC and injected into AC system through the neutral point of a zigzag transformer at the sending end. At the receiving end, DC power is received from the neutral point of another zigzag transformer and it is converted to AC before feeding to the infinite bus. The zigzag connections are used at the secondary and primary sides of sending end and receiving end transformers, respectively. The main purpose of the use of zigzag connected winding is to avoid the magnetic saturation of transformer due to DC. The saturation is avoided as two fluxes produced by the DC current flowing through each of the windings in each limb of the core of a zigzag transformer are equal in magnitude and opposite in direction. Therefore, the net DC flux in each limb at any instant of time is zero.

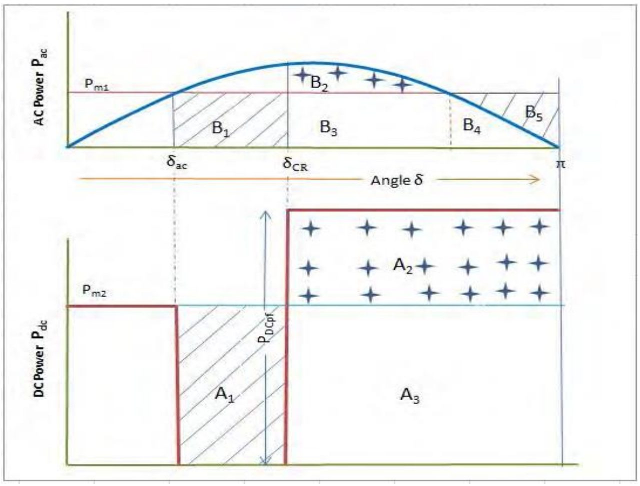


Fig.2.1.Simultaneous AC and DC power flow curve

$$A_1 + B_1 = A_2 + B_2 - B_5$$

During the fault condition the transmission line does not transmit any power. That is, the electrical power consumption is zero. However, during this period mechanical system continues to produce energy and due to this mechanical energy generation during the fault the whole system may be unstable. To attain a stable condition, after clearing the fault the electrical system must consume an additional amount of energy which is equal to the mechanical energy generation during the fault. That is, for the stability of the system.

Mechanical energy generation during the fault is equal to Additional electrical energy consumption right after clearing the fault.

$P_{ac} + P_{dc} = P_m$

$$T_{CR} = T_{cr}\sqrt{\left(1-\frac{P_{comb}}{P_{DCpf}+\bar{P}_{acm}}\right)\left(\frac{\delta_m-\delta_{ac}}{\delta_{cr}-\delta_0}\right)\frac{P_l}{P_{comb}}}$$

$$\delta_{cr} = \delta_m - \frac{P_{comb}}{P_{DCpf}+\bar{P}_{acm}}(\delta_m-\delta_{ac})$$

$$T_{CR} = \sqrt{\frac{4H(\delta_{CR}-\delta_{ac})}{\omega_s P_{comb}}}$$

3. SVPWM CONTROLER

Because of the constraint that the input lines must never be shorted and the output current must always be continuous a voltage source inverter can assume only eight distinct topologies. Six out of these eight topologies produce a nonzero output voltage and are known as non-zero switching states and the remaining two topologies produce zero output voltage and are known as zero switching states.

The desired three phase voltages at the output of the inverter could be represented by an equivalent vector V rotating in the counter clock wise direction as shown in Fig. 3. The magnitude of this vector is related to the magnitude of the output voltage is shown in Fig.4 and the time this vector takes to complete one revolution is the same as the fundamental time period of the output voltage.

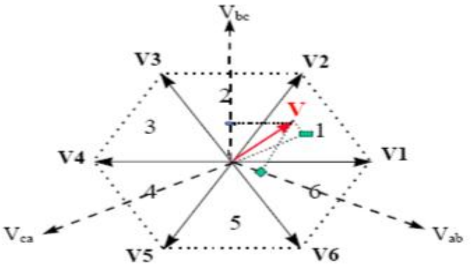


Fig 3. Output voltage vector in the $\alpha-\beta$ plane

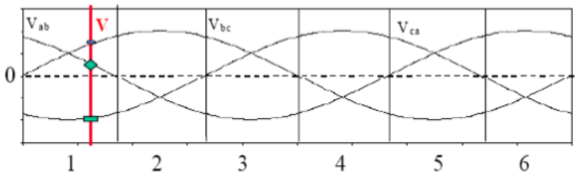


Fig 4.Output line voltages in time domain

4.APPLICATION OF PROPOSED MODEL

Montana 500kV transmission system

Montana 500 kV transmission line is used to transmit power from East, Colstrip, to west, Taft. The eastern Montana generation system has four coal-fired thermal units of 2272MW. The necessary parameters of the transmission system are presented in table 3. The stability analysis considers a maximum power flow condition keeping the recommended stability margin of 30% for HVAC long transmission line [4]. In this condition, the load flow study provides a power flow of 1028 MW at an angle of 44.47^0. With this pre-fault steady state condition and a 3-phase to ground fault at the load terminal of the sending end bus the stability analysis for pure AC system shows a CCT of 175ms. In case of simultaneous AC-DC transmission system, critical clearing times are evaluated for different percentage of DC voltage mix and different transmission angles of simultaneous AC-DC system. During the variation of DC voltage mix a constant transmission angle of 44.47^0 of AC power flow and during the variation of transmission angle a constant DC voltage mix of 49.5% are considered.

Loadability Analysis

The possible maximum power transfer through the 500 kV Montana transmission line is evaluated considering two different systems of power transmission; (i) pure AC (ii)simultaneous AC-DC power transmission system.

Impact of the variation of DC voltage mix on the combined power flow

In this section the impact of variation of DC voltage mix, in a simultaneous AC-DC system, on the total combine power flow is evaluated and the results are compared with the pure AC system.

In this section it is presented that in an AC system, line cannot be loaded up to its thermal limit. However, in AC-DC system the magnitude of the current through the line can be up to its thermal limit. In Table 1 the total power flow transmitted through the line for both the cases are compared. Note that, in the evaluation of the maximum power flow in a pure AC system 30% steady state stability margin [1] is considered.

Fault type-1: Three -phase to ground fault at the load terminal near the sending end bus of the transmission line.

The developed model is applied to the simultaneous AC-DC system considering same fault and steady state loading like as pure AC system analysis. Note that, pure AC system analysis is performed considering 1028 MW of power flow and the obtained critical clearing time is 175ms. The critical clearing time obtained through developed model is compared with those obtained in pure AC system. The results are shown in Table 1 and Table 2.

Table.1: Steady state power flow for different transmission angle

δ (˚)	Pcomb (MW)	P (MW)	Increased loadability (%)	Critical clearing time(ms)		Increased stability (%)
				TCR	Tcr	
20	2677	1028	160	408	175	133
25	2643	1028	157	402	175	129
30	2608	1028	153	395	175	125
35	2572	1028	150	388	175	121
40	2535	1028	146	382	175	118
45	2497	1028	142	375	175	114
50	2458	1028	139	367	175	109
55	2417	1028	135	360	175	105
60	2375	1028	131	353	175	101
65	2331	1028	126	345	175	97

The stability analysis presented in Table 1 considers 49.5% of DC voltage mix.The evaluated critical clearing time for different transmission angle clearly indicates that the higher the transmission angle the lower the stability improvement. It indicates that with the higher AC power flow in a simultaneous AC-DC system the system will remain stable only for lower duration of fault. The stability improvement varies from 133% to 97% for the transmission angle variation from 20^0 to 65^0 respectively.

Table 2; Steady state power flow for different DC voltage mix

Vdc Mix (%)	Pcomb (MW)	P (MW)	Increased load-ability (%)	Critical clearing time(ms)		Increased stability (%)
				TCR	Tcr	
05	1226	1028	19	233	175	33
10	1395	1028	35	275	175	57
15	1573	1028	53	309	175	76
20	1716	1028	66	325	175	85
25	1850	1028	79	338	175	93
30	1990	1028	93	348	175	98
35	2127	1028	106	357	175	104
40	2259	1028	119	365	175	108
45	2389	1028	132	371	175	112
50	2501	1028	143	376	175	114

In Table 2, it is observed that the transient stability of a system with long transmission line can be improved through simultaneous AC-DC power transmission system and the stability improvement is increasing in nature with the increase in the DC voltage mix for a fixed transmission angle. It indicates that at higher DC voltage mix the system will remain stable for higher duration of the existence of the fault. In this case the transmission angle is considered as 44.47^0. The improvement in the critical clearing time varies from 33% to 114% for the DC voltage mix variation from 5% to 49.5%, respectively.

Tables 1 and 2 show that the critical clearing time can be increased by decreasing the transmission angle of AC power flow of simultaneous AC-DC system and increases by increasing dc voltage mix in simultaneous AC-DC power transmission system.

Loadability increases by increasing dc voltage mix in simultaneous AC-DC power transmission system and decreases by increasing the transmission angle in simultaneous AC-DC power transmission system.

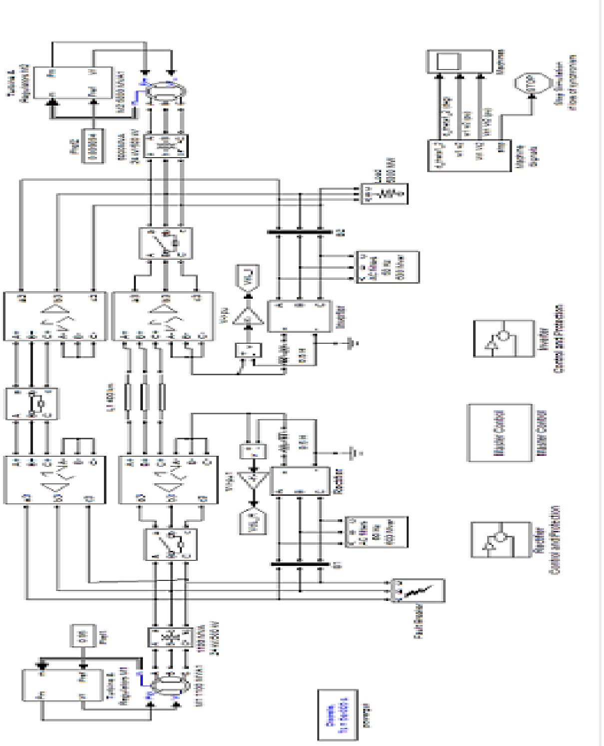
Table3:Parameters of Montana 500 kv transmission sym

S. No	Component	Parameter
1.	Line	i)x = j253.21Ω/phase/ckt. ii)single ckt, iii)Three phase iv)60Hz, v)804 km, vi)500 kV vii) Thermal limit current = 3 kA
2.	Generator	358*2, 778*2(MW),24 kV, Reactance = 0.3pu, H = 3.5 s.
3.	Generator Transformer	24/230 kV, Leakage reactance = 0.15 pu.(Pure AC)
4.	Transformer (At the send -ing end of the line)	Δ-Y, 230/500 kV, leakage reactance = 0.1 pu. (pure AC),Δ-Z, 230/253 kV, Leakage reactance = 0.1 pu. (AC- DC)
5.	Transformer (At receiving end line	Z-Δ , 253/500 kV, Leakage reactance= 0.1 pu, (AC-DC)
6.	DC system	DC system rated voltage and current are 202 kV and9 kA, respectively.

Parameters of the different components of a transmission system considered for circuit simulation

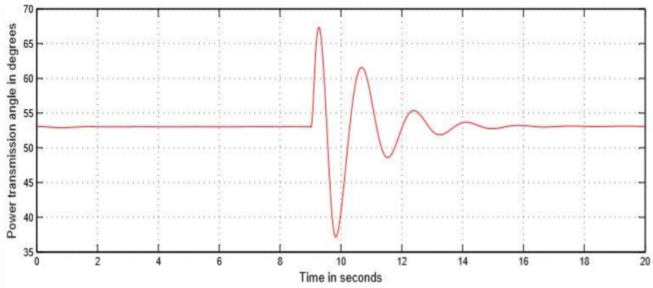
S. No	Component	Parameters
1	Line	(i) z = 0.01755 +j0.3292 Ω/km/phase ,(ii)Single ckt. (iii)Three phase,(iv)60 Hz,(v)400 km,(vi)345 kV (vii)Thermal limit current = 1.8 kA ACSR twin bundle conductor
2	Generator	1100 MVA, 24 kV, 60 Hz, H = 7 s, the parameters on its own base Xd = 1.305 , Xd′ = 0.3 ,$Xd^{¨}$=0.3 , Xq = 0.474 , Xq″= 0.243 , X = 0.18 , Stator resistance Rs =0.00285 , Td′ = 1.01 s, Td = 0.053 s , Tqö =0.1 s ,
3	Generator Transformer	1100 MVA, 24/132 kV, 60 Hz, 10% reactance.
4	Transformer (At the sending end of the line):	Δ-Y, 1100 MVA, 132/345 kV, 60 Hz, 16% reactance. (pure AC),Δ-Z, 500 MVA, 132/172.5 kV, 60 Hz, 16% reactance.(AC-DC)
5	Transformer (At the receiving end of the line):	Y-Δ , 1100 MVA, 345/132 kV, 60 Hz, 16% reactance. (Pure AC),Z-Δ , 500 MVA, 172.5/132 kV, 60 Hz, 16% reactance(AC-DC)
6	DC system	The Rectifier and Inverter are 12-pulse converters using two 6-pulse thyristor bridges connected in series, DC current (rated) = 5.4 kA, Smoothing reactor=0.5H,Rectifier firing angle (minimum) =5^0, Inverter Extinction angle(minimum)=14^0
7	Excitation system	Ka = 200, Tr = 0.02, Ta = 0.001, Ke = 1, Kf =0.001, Tf=0.1, Kp = 0, Efmin = 0, Efmax = 7, Vt0 = 1, Vf0 =1.4.

Simultaneous AC-DC system Circuit Model Using MATLAB Simulink With Single Circuit Transmission

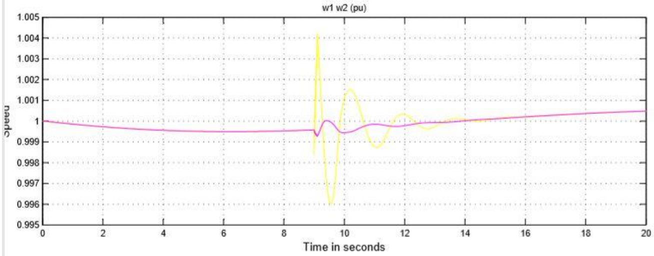


Rotar angle transient response of monata 500kv transmission system for different values of steady state angle.

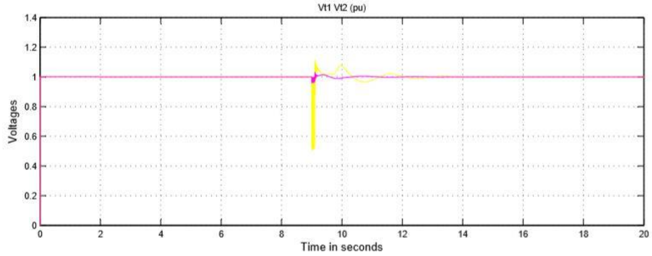
For 30^0



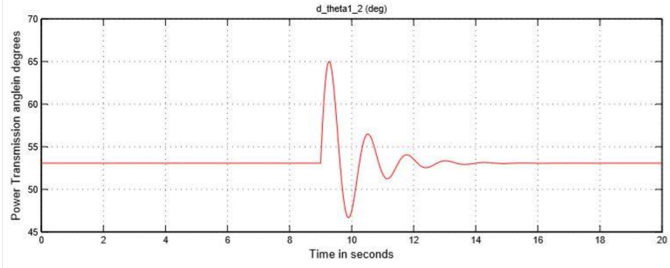
Speed response



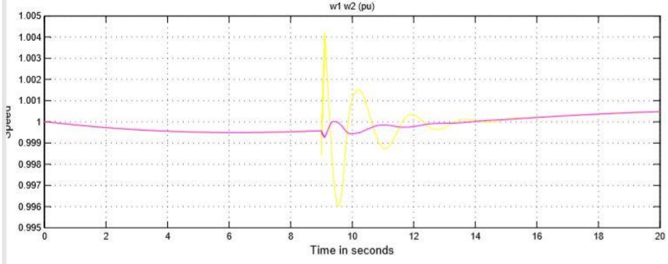
Voltage response



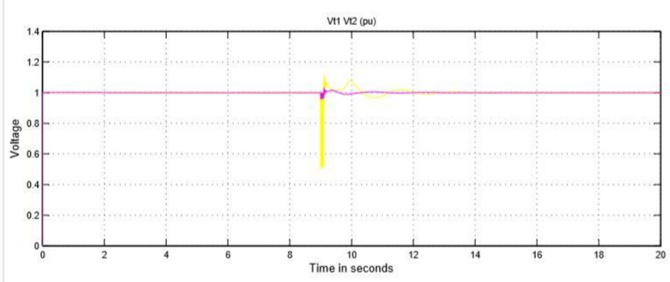
For 50^0



Speed response



Voltage response



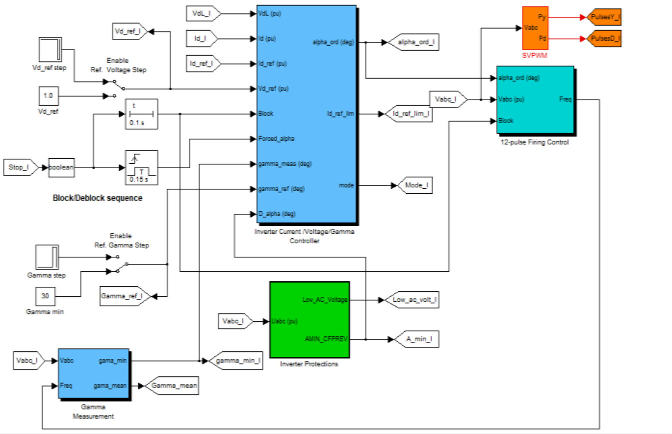
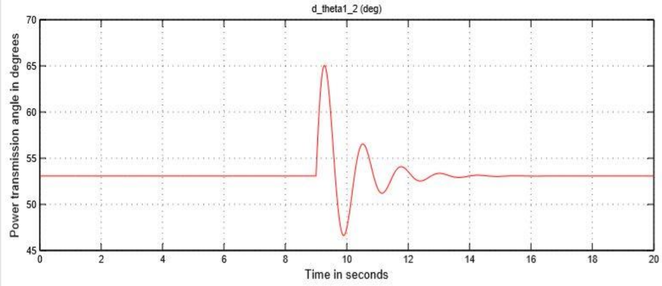
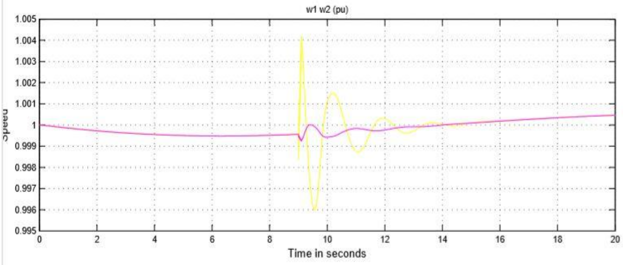


Fig 5.Block diagram for SVPWM controller

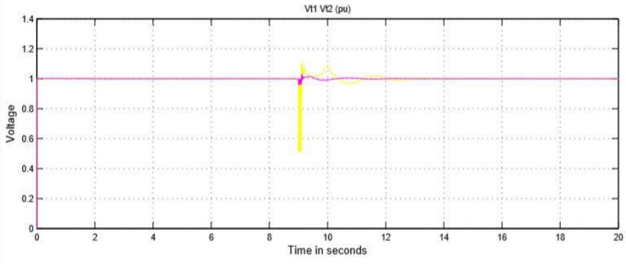
Transient response by using SVPWM controller For 30^0 steady state angle



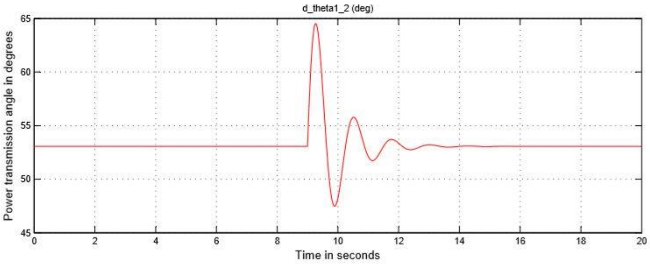
Speed response



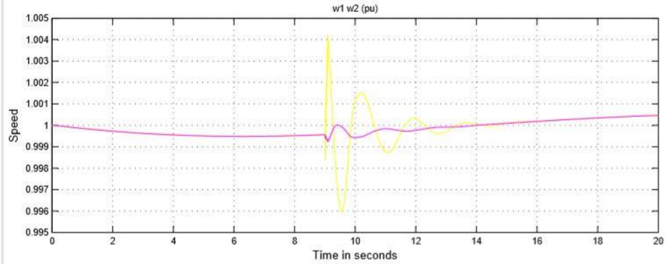
Voltage response



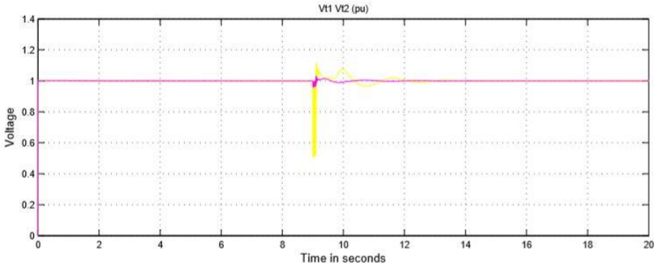
For 50^0



speed response



Voltage response



CONCLUSION

Load carrying capability and stability of an existing AC transmission system can be increased through simultaneous AC-DC power transmission system. As the conventional approaches have limited scope to improve the performance of existing AC transmission system the simultaneous AC-DC system has attracted research interest considerably. Existing AC transmission line can be converted into simultaneous AC-DC transmission line without changing line infrastructures at all.

To date, the advantages of simultaneous AC-DC power flow through the existing AC line have shown through numerical simulation without the development of any generalized mathematical model. This paper presents a generalized analytical model of a simultaneous AC-DC power transmission system for loadability and stability analysis. The model incorporates some factors among AC and DC currents and voltages and establishes the correlation among the factors and other parameters of the system appropriately. The process of model development also includes SVPWM controller for better fundamental output voltage. It is expected that the model can be an analytical tool for power transmission expansion planners and designers. The validation of model through different approaches clearly shows that the results obtained using the proposed model are close to the published ones as well as to those obtained through circuit simulations using standard software. The application of proposed model in an existing AC transmission system reveals that the maximum power flow and the critical clearing time for a severe most fault at different locations of a simultaneous AC-DC system are higher than those of same pure AC line. This finding justifies the finding of the published numerical simulation. Higher amount of transient stability (critical clearing time) is achieved in a simultaneous AC-DC system by exploiting the short time overloading feature of converters after clearing the fault.

LIST OF ABBREVIATIONS:

Eg - Internally generated voltage of the generator, Er-Receiving end voltage, Eφm- Maximum phase voltage of pure AC system, H- Inertia constant of the generator, Pl-Steady state power flow through pure AC line, Pcomb-Combined steady state AC-DC power flow, Pac -Steady state AC power in simultaneous ACDC system, Pdc- Steady state DC power in simultaneous AC-DC system, PDCpf-Post-fault DC power flow, PDcad- Additional DC power flow during post-fault condition, Pacm- Maximum value of the AC power in simultaneous AC-DC system, Tcr- Critical clearing time for pure AC system, TCR -Critical clearing time in simultaneous ACDC system, Vdc- DC voltage in simultaneous AC-DC system, Xgr -Summation of Xte and XTr, Xte- Reactance of generator and transformer, XTr-Reactance of transmission line, ωs -Angular frequency, δ0-Pre-fault steady state torque angle in case of pure AC system, δcr- Critical clearing angle for pure AC system, δac-Torque angle due to AC power transfer in simultaneous AC-DC system, δCR- Critical clearing angle in simultaneous ACDC system

δm- Maximum rotor angle.

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