Characterization and Transient Analysis of AC Link with Half Wavelength Line Properties under Critical Fault Condition

J.A. Santiago Ortega, M.C. Tavares.

***Abstract*-- An alternative for very long distance transmission is the AC link system based on half wavelength (HWL) properties that naturally has around 2600 km for 60 Hz system. Adequate response under fault conditions is a critical design issue for transmission systems. One important drawback of this kind of transmission system is the high overvoltage produced when a three-phase fault takes place at critical region. This paper presents a study of a natural HWL line with 2600 km showing the severity of overvoltage and the transient behavior characteristics when critical three-phase fault is applied. The main contribution of the paper is the analysis of effects of typical factors (short circuit level and loading level) and real transposition representation on the voltage characteristics when critical fault is applied. Besides, it is proposed a mitigation procedure that modifies the resonance condition and attenuates overvoltages during a critical fault until the protection system acts. It is shown that without any mitigation procedure the typical protection time response is not adequate.**

***Keywords*: Long distance transmission, half wavelength line, fault, overvoltage, electromagnetic transient.**

I. Introduction

THE increasing of electric energy demand creates the necessity of reinforcing and expanding power systems to transport energy from expanded or new power sources. As new potential sources are usually located far away from main load centers, power system requires the construction of bulk transmission systems over very long distances. This is a specific problem for continental countries like Brazil, China and Russia.

In last decades requirements of very long distance transmission resulted in High Voltage Direct Current (HVDC) transmission systems being built, mainly because of the technological evolution in power electronics and the many years of experience. However, classical HVDC transmission system based on Line Commutated Converters (LCC) has some operational limitations, such as coarse reactive power control, inability to work in weak system without dynamic reactive power support, limited voltage regulation, difficulty to achieve low reverse power transfer for emergency conditions, non-independent black start capability for wind farms [1,2], and in some cases it needs extended grounding return system and high level of harmonic filter system.

The transmission line with a little more than half wavelength (HWL+) is an Alternating Current (AC) point to point transmission system that presents interesting properties for bulk power transmission over very long distances. HWL+ lines maintain the voltage at line ends near 1.0 p.u. regardless of the loading level. This occurs because this line does not act as a generator or a sink of reactive power energy [3,4], so transmission system with HWL+ properties does not need additional reactive power support. In addition, HWL+ has good steady state stability properties, as it behaves as a "short line" from the voltage terminals point of view [4,5]. These specific properties of HWL+ system could be outstanding for bulk power transmission attending renewable energy sources like intermittent energy sources, which have variable power profile.

Preliminary studies show that cost per unit length of natural HWL+ line is much smaller than the conventional AC compensated transmission lines and even 25% lower than HVDC line with similar power capacity [6,7]. Other profitable feature of HWL+ line is the lower overvoltage level for switching transients [8,9]. A HWL+ line has naturally around 2600 km length for 60 Hz system. However it is possible to have artificial HWL+ lines with flexible distance when tuning banks based on inductive and capacitive components are considered [10].

AC link based on HWL+ transmission system was studied for many years; however it has not been implemented in a real system. In recent years HWL+ transmission lines has attracted the attention of researchers in Brazil to transmit hydropower from Amazon basin to Southeast/Northeast load centers and in China to transmit energy from Xinjiang to Eastern coastal areas [11].

One important problem still to be solved for HWL+ is the high overvoltage produced when a three-phase fault takes place at critical regions along the line [5]. Adequate protection system response under this fault conditions is a critical design issue [12,13,14].

This paper presents a study of a HWL+ line with 2600 km showing the voltage level severity and the transient voltage profile when three-phase fault is applied on critical locations. First, the critical fault location is characterized considering loading levels, real transposition representation and strength of equivalent power system at both ends of line. Eventually, as the mechanism that produces the overvoltage is a resonance condition at fundamental frequency, a mitigation procedure is presented to reduce the overvoltage until protection system

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acts. The simulations and study are made with PSCAD/EMTDC simulation tool.

II. DESCRIPTION OF TEST SYSTEM

A. Transmission system

The HWL+ transmission system is designed for bulk power transmission, for which a high surge impedance level (HSIL) line should be considered. For the present study a transmission line of 800 kV with 2600 km at 60 Hz was used. The bundle geometry was optimized to achieve 4745 MW [15]. This non-conventional line has 8 conductors type Bunting per phase and two ground wires (type EHS 3/8"). It has an asymmetrical bundle configuration with different central phase geometry, as shown in Figure 1. The resistivity of soil is 2000 ohm.m. Table I shows the electrical parameters for 60 Hz (considering a balanced line).

The influence of properly representing the line transposition section was considered. The line was represented using non-transposed section with the transposition tower. The 2600 km line is split into 9 transposition cycles of 288 km each one. Each cycle is divided into 4 sections of 48 km, 96 km, 96 km and 48 km.

This line was implemented in PSCAD/EMTDC software with frequency dependent phase model.

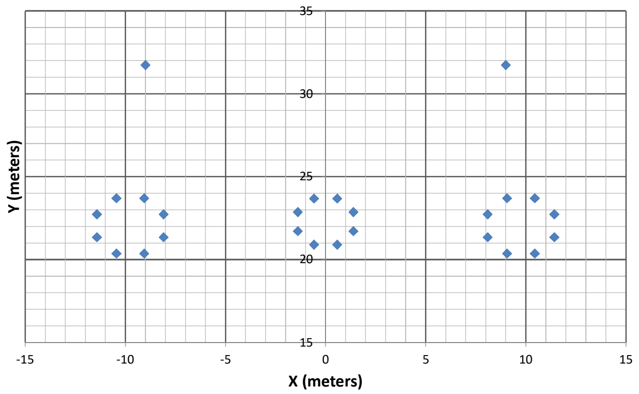


Fig. 1. Geometry of tower. Mean conductor´s heigth.

TABLE I
TRANSMISSION LINE PARAMETERS

Electrical parameters		
Zero sequence		
R0 (ohm/km)	X0 (ohm/km)	B0 (µS/km)
0.3871	1.3502	4.066
Positive/negative sequence		
R1 (ohm/km)	X1 (ohm/km)	B1 (µS/km)
0.0068	0.1737	9.5367
Electromagnetic parameters		
γ (km^{-1})	$\alpha + j\beta = 0.0000254 + j\,0.0012873$	
Z_C (ohm)	134.98 - j 2.66	
SIL (MW)	4745	
λ(km)	4882	

B. Power system at terminal ends

The transmission system analyzed connects a hydroelectric generation source to a power system. In the study the sending end was represented by a generation station with 11 synchronous machines and 11 step-up transformers which resulted in 9.6 kA of three phase short circuit current (Scc). The parameters of each individual machine are based on a real generation station (Serra da Mesa in Brazil). The receiving end was connected to an equivalent network at 500 kV with typical three phase Scc of Brazilian power system. Two Scc levels are considered for the receiving end: 40 kA (strong point connection) and 15 kA (weak point connection). To calculate the positive sequence and zero sequence parameters of equivalent sources, the following typical Brazilian system data were used: X1/R1=6, X1/X0=0.2 and X0/R0=5. A step-down transformer of 800/500 kV is used, as shown in Fig 2.

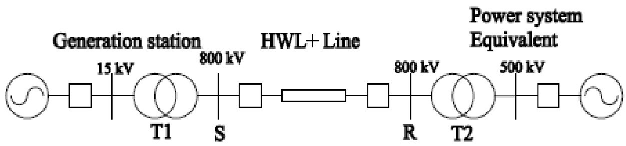


Fig. 2. Test power system.

TABLE II
POWER SYSTEM PARAMETERS

Source equivalent impedances			
Source		**Zero Sequence (Ω)**	
Sending – 15 kV		0.000754 + j 0.025904	
Receiving strong – 500 kV		7.2169 + j 36.084	
Receiving weak – 500 kV		28.868 + j144.34	
Source		**Positive Sequence (Ω)**	
Sending – 15 kV		0.000754 + j 0.025904	
Receiving strong – 500 kV		1.1864 + j 7.1187	
Receiving weak – 500 kV		4.7458 + j 28.475	
Equivalent transformer			
Transformer	Xr(%)	kV	Total MVA
T1	11.84	800/15	5197.5
T2	10.00	800/500	4500.0

C. Power system operation condition

The system is tested under different loading conditions. It is important to notice that in real AC power systems, basic control variables for transmission line operation mode are the module of voltage at ends and the angle difference between voltage ends. In this case, for normal operation condition the main objective is to maintain 1.0 p.u. at receiving end busbar without overvoltage along the line.

Setting the voltage and the loading condition at receiving end, and using the two-port network theory, the voltage and current at sending and receiving ends are determined. Therefore, initial voltage and loading conditions at receiving end is associated to a voltage value at both sources. Table III shows the voltage (module and angle) of internal equivalent sources (behind the equivalent impedance) for every loading condition studied. It is important to notice that there is no reactive power transferred to receiving end.

TABLE III
VOLTAGE OF EQUIVALENT SOURCE

Load	Case: Weak Reception Terminal				Case: Strong Reception Terminal			
	|Vs|	< Vs	|Vr|	< Vr	|Vs|	< Vs	|Vr|	< Vr
p.u.	kV	(º)	kV	(º)	kV	(º)	kV	(º)
0.1	13.6	185.9	498.3	-1.3	13.6	187.3	499.5	-0.3
0.5	14.7	199.0	493.9	-6.4	14.6	199.9	497.9	-1.6
1.0	16.9	212.2	494.0	-12.8	16.5	213.2	496.2	-3.2

III. FAULT SIMULATION AND RESULTS

In conventional AC systems the strength of source influences on the short circuit currents levels. It is also very important to learn how terminal equivalent contributes to HWL+ behavior under fault. In order to study the voltage profile due to three phase fault the two receiving systems are considered: strong and weak. Additionally, it is analyzed that fault could be applied when transmission system is carrying 0.1 SIL, 0.5 SIL and 1.0 SIL. The three phase faults are applied along the line and for each fault location we measured the voltage along the line. Fault resistance is taken as 10 ohm.

It is important to notice that line model does not consider disruptive discharge along the line for high voltage level, or corona effect. This simplified model permits identification of critical regions and the overvoltage severity. However such an extreme high voltage would not occur in real cases.

Formerly loading level influence is analyzed when three phase fault is applied. Fig. 3 shows the maximum sustained voltage levels per phase produced when permanent three phase fault is applied along the line for different loading levels when reception is connected to a stronger source. There is a little unbalance among phases due to real transposition representation. The maximum voltage level does not occur in the same point of fault, but anywhere along the trunk. It is observed that maximum overvoltage level increases with loading level. However the critical fault region does not change with loading level.

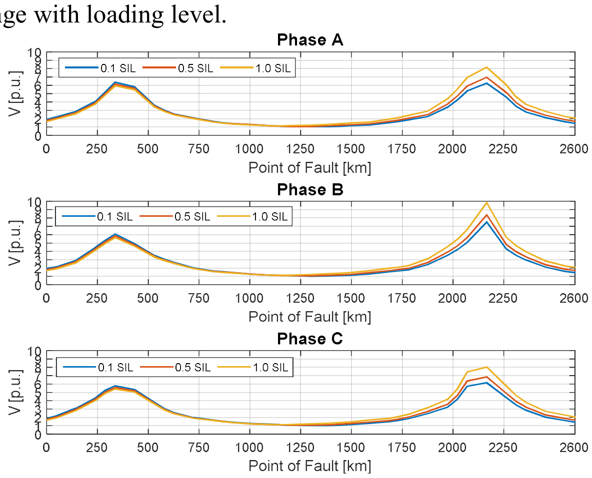


Fig. 3. Maximum voltage level when three phase fault is applied at each point along the line for different loading condition - Strong source at receiving end. Maximum voltage does not apear at the same point of fault, but anywhere along the trunk.

Three phase fault resonant location is defined by the strength of equivalent source at the remote terminal [16]. In this study case it is possible to observe two critical regions derived by the two equivalent terminal sources. The sending end produces a resonant point at 81% of length line measured from sending end and the maximum overvoltage for faults at this point is 9.83 p.u. for 1.0 SIL of loading. However, for light loading (0.1 SIL) the maximum voltage reached is 7.51 p.u. The receiving end connected to a stronger power system produces a resonant point at 87% of length line measured from receiving end and the maximum overvoltage for faults at this point is 6.10 p.u. and practically does not vary with loading.

Fig. 4 shows the maximum overvoltage for faults applied along the line when receiving end is connected to stronger power system and weaker power system for 1.0 SIL of loading. As the source at sending end does not change, the resonant point associated to this source does not change either. However, the resonant point of receiving end changes from 87% for strong power system to 76% for weaker power system. Therefore, weaker sources move the resonant point towards central region.

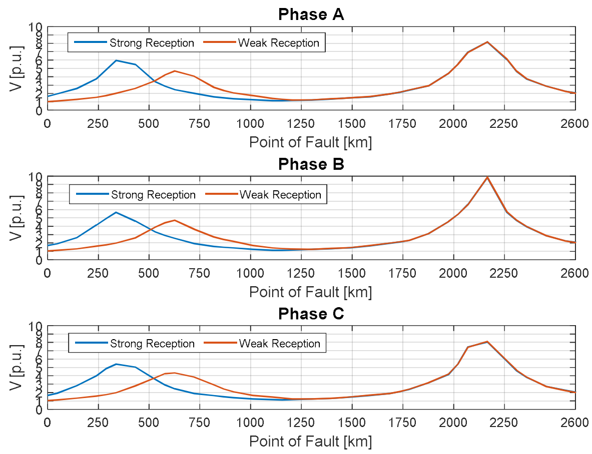


Fig.4. Maximum voltage level to three phase fault along the line for 1.0 SIL.

Fig. 5 shows the sustained voltage profile when permanent fault is applied on the critical resonant point located at 81% of line length from sending end (kilometer 2160) with 1.0 SIL. The maximum overvoltage occurs around kilometer 1000. Overvoltage level is not constant and it occurs practically all over the line. The voltage unbalance among phases is due to real transposition effect.

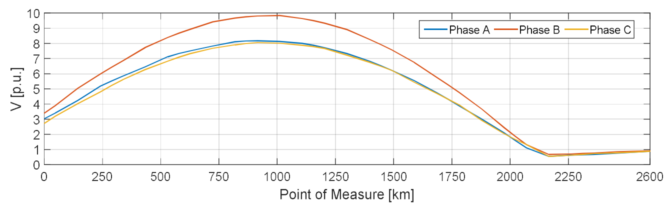
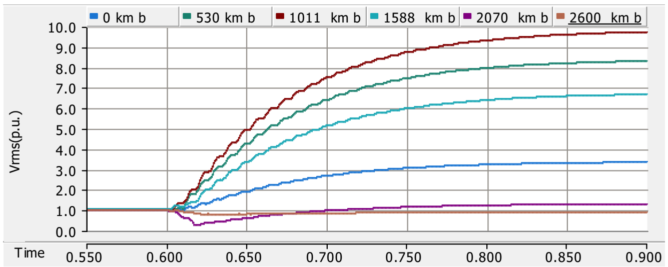


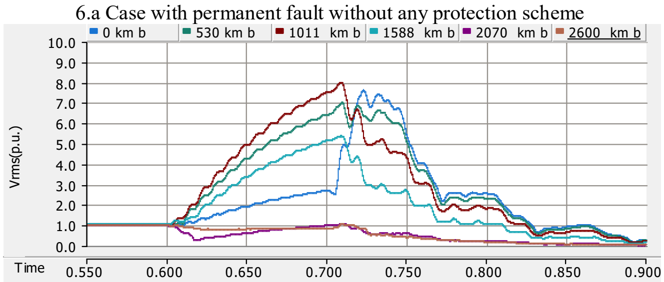
Fig. 5. Voltage profile for three phase fault at resonant point (km 2100) for 1.0 SIL.

Fig. 6 shows the variation in time of rms voltage of phase B (phase with highest values) on different points along the line

(0 km, 550 km, 1011 km, 1588 km, 2070 km and 2600 km). The fault is applied at critical resonant point located at 81% of line length from sending end at 0.6 seconds. Fig.6.a shows the ideal case without any protection action in order to see that maximum values are higher than those present in conventional lines. Fig. 6.b. shows the ideal case with permanent fault with protection taking place after 100 ms. It is possible to verify that extremely high overvoltages will appear [14]. The maximum values in each location are reached in 250 ms. The voltage rate of change is very high at the beginning of the fault. A large region between the sending end and the fault location reaches voltage level higher than 2.0 p.u in 50 ms. This is a very severe condition that can jeopardize circuit-breaker operation [17] and compromise the line insulation.



6.a Case with permanent fault without any protection scheme

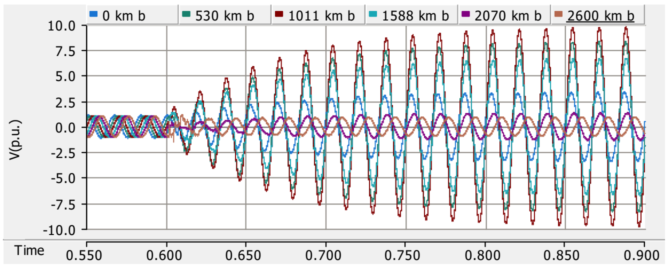


6.b. Case with permanent fault and protection triping at 100 ms.

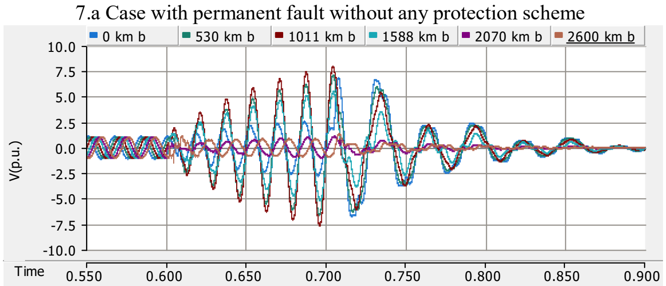
Fig. 6. RMS Phase B Voltage variation for three phase fault at resonant point.

Fig. 7 shows phase B voltage waveform on different points along the line for three phase fault applied on critical resonant point. Fig.7.a shows the ideal case without any protection action. It is seen that transient behavior is very different from that present in conventional lines, as the high harmonic transients will vanish quickly and basically only fundamental frequency response will be present. This confirms that fundamental frequency resonance produces three phase fault overvoltage. Fig. 7.b. shows the ideal case with permanent fault with protection tripping the line after 100 ms. Although protection acts, the overvoltage would be higher than regular insulation levels. Peak values higher than 2.0 p.u. are reached in one cycle.

Fig. 8 shows the active and reactive power at sending (PMWS, QVARS) and receiving end (PMWR, QVARR) during the permanent three-phase fault applied on resonant point at 81% of line (measured from sending end). Supposing there is an ideal source at sending end contributing to this resonant condition, this source provides active and reactive power necessary to these very high overvoltages. If no mitigation action and protection scheme is applied rapidly, the active power could reach up to 8 SIL and reactive power more than twice the active power. The negative sign of reactive power means that transmission line provides reactive capacitive power that is associated with high voltage levels along the line. Obviously, mitigation and/or protection actions must be fast enough to avoid the overvoltage and high levels of active and reactive power.

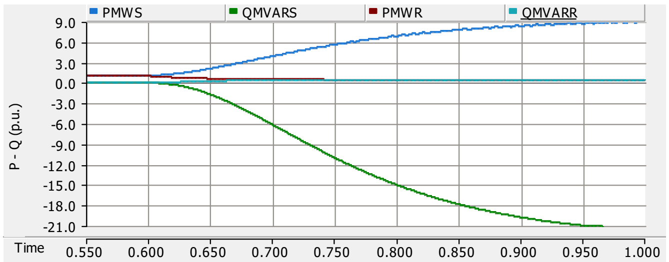


7.a Case with permanent fault without any protection scheme

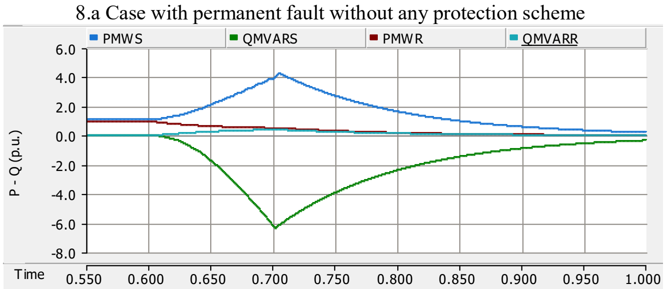


7.b. Case with permanent fault and protection triping at 100 ms.

Fig. 7. Phase B Voltage waveform along the line for three phase fault at resonant point.



8.a Case with permanent fault without any protection scheme



8.a Case with permanent fault and protection triping at 100 ms.

Fig. 8. Active and reactive power variation during three phase fault at critical point. Power capacity of sources are considered ideal.

In conventional AC systems, critical condition requires that protection acts fast enough and clears the fault to avoid damage to equipment. For this study 100 ms dead-time was accepted in order to evaluate overvoltage mitigation method.

As high voltage levels are associated to reactive capacitive power, it is expected that the mitigation procedure is based in reducing this reactive power flow. Therefore, we propose the insertion of shunt reactor when critical fault is applied in order to avoid the resonant condition and reduce the voltage, minimizing active power and reactive power levels.

The specification of size and location of reactor considers:

a. Reduction of overvoltage level and reactive power flow.

b. Avoid producing other resonant point for the other source (at receiving end of line).

The basic condition is to minimize reactive capacitive energy produced by line and overvoltages values that are several per unit quantities. Therefore, a shunt impedance with value similar to line characteristic impedance will produce the necessary inductive capacitive energy.

The optimum shunt reactor has an impedance equal to line characteristic impedance, Zc = 135 ohm (358 mH) and should be located at 500 km from sending end. A quality factor of 400 (typical Brazilian shunt reactor factor) was adopted.

In this case, as overvoltage along the line has a high rate of rise, the shunt reactor needs to be connected in 1 to 2 cycles. This could be performed with rapid circuit breakers or through a spark gap trigged at 2.0 p.u. phase to ground voltage. In the present study a voltage controlled switch was used. The shunt reactors was inserted at 0.6123, 0.6108, 0.6153 ms, for phases A, B and C, respectively.

Fig. 9 shows the active power and reactive power during the three phase fault using the mitigation procedure proposed. The active and reactive power of both sources have moderate variations. Reactive power at sending end increases to 0.8 p.u. for 50 ms and then it decreases after mitigate procedure operates.

Fig. 10 shows the variation in time of rms voltage of phase B at different points along the line. The fault is applied at critical resonant location at 87% of line length from sending end at 0.6 seconds. The maximum values in each location are reached in 40 ms after fault application and then started to decrease. Maximum overvoltage occurs on 1000 km from sending end and it reaches 3.0 p.u in 50 ms approximately. When protection system acts after 100 ms the voltage levels will have a gradual reduction.

Fig. 11 shows the voltage waveform of phase B for three phase fault applied on critical resonant location. Peak values between 2.0 and 3.0 p.u. occur around kilometer 1000 from sending end. These values will reduce after around 3 cycles and fault can be eliminated within 100 ms.

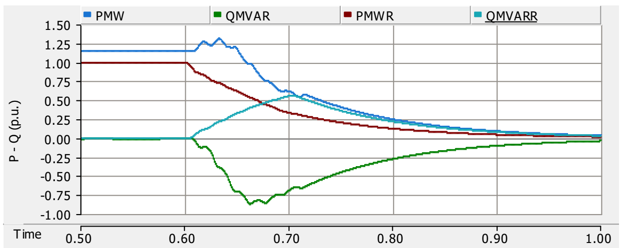


Fig. 9. Active and reactive power variation during three phase fault at critical location using shunt reactor as mitigation procedure. Sources' power capacity is considered ideal.

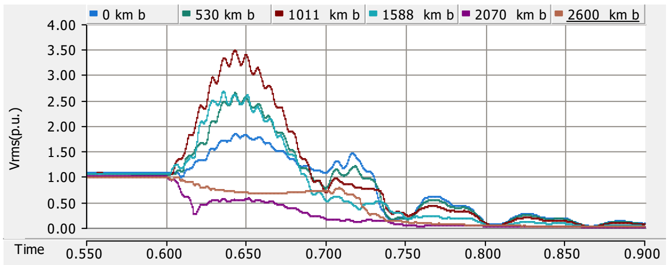


Fig. 10. RMS Phase B Voltage variation for three phase fault at resonant point using mitigation action.

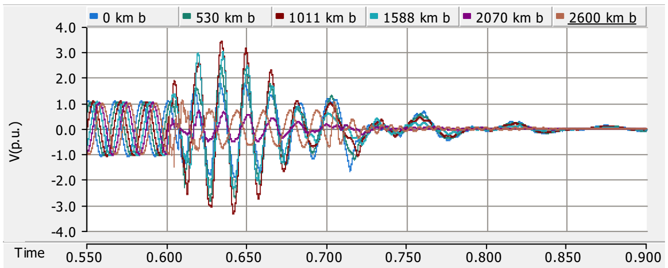


Fig. 11. Phase B Voltage waveform for three phase fault at resonant point using mitigation action.

Ongoing research will present in near future specific studies on shunt reactor.

IV. Conclusions

The HWL+ transmission system is an AC alternative to bulk power transmission over very long distance due to its robust properties in normal operation condition. However, fault characteristics are different from those of a conventional AC transmission system with few hundred kilometers length.

This paper shows the characteristics and voltage levels severity when three phase fault is applied in critical regions. Apart from these critical regions, three phase faults cause moderate overvoltage along HWL+ trunk. Additionally, it is very important to learn that three phase faults are rare events.

However if critical three phase fault occurs, a mitigation procedure should promptly be implement to remove the system from positive sequence fundamental frequency resonance condition. Very high overvoltages will occur along the trunk. This overvoltage could reach several times the nominal value.

This work shows that overvoltage maximum values are influenced by transmission line loading level, observing that higher loading levels produce higher overvoltage levels. There are two critical points on a HWL+ transmission system, each of one associated with each terminal equivalent system. Also this work shows that location of critical point depends on the strength of equivalent power system and is located between 76% (weaker power system) to 87% (stronger power system) from source terminal. Weaker sources move the critical point fault toward to center of the HWL+ line.

For critical fault condition, the maximum overvoltage does not appear on the same point of fault location, but it appears approximately at middle distance between terminal and fault point. The phenomenon is basically a fundamental frequency transient, and overvoltages will reach very high values within very short time, in the range of 250 ms if any protection action is implemented. At the same time active and reactive power reach very high values. These characteristics are very different from those found in conventional lines under fault conditions. Therefore, mitigation procedure should operate fast enough, as magnitudes higher than 2.0 p.u will be produced in very short time, around one cycle. The time to reach the maximum values depends on system parameters.

This work presents a mitigation procedure to reduce overvoltage during a critical fault that consists in introducing a shunt reactor to reduce reactive power levels. The shunt reactor could be connected through very fast circuit-breaker, that should operate in less than 2 cycles. Another alternative would be a spark gap that would be trigged for voltages above 2.0 p.u..

The shunt reactor manage to remove the system from the resonant condition in less around 50 ms, enabling safe circuit-breaker operation.

Further studies about shunt reactor will be presented in the near future.

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