Sensitivity Analysis in the Transient Recovery Voltage in an Industrial Power System

R. S. Ferreira

***Abstract*—Transient Recovery Voltage (TRV) is one of the electromagnetic studies which shall be carried out to verify if the circuit breakers can withstand the transients imposed by the electrical system. Normally, the transient studies are performed only at the final phases of the electrical system design and if a problem exists mitigation measures shall be taken. In some cases, these measures imply in more costs and physical space in the electrical substations. In offshore units, the weight and space intended to be used are limited and if mitigation measures are necessary, it is important to know them as soon as possible. Therefore, this paper aims at verifying the influence of certain parameters on the transient recovery voltage of an industrial offshore electrical power system. Simulations are performed in a typical offshore installation and the effects in the different voltage levels (13.8 kV and 4.16 kV) are analysed. The results are intended to give a first approximation of the main parameters that affects the peak and rate of rise of the transient recovery voltage during the initial phases of the electrical system design.**

***Keywords*: Transient Recovery Voltage (TRV), Industrial Electrical System, Overvoltages.**

I. Introduction

THE transient voltage that appears between the poles of the circuit breaker during its opening is called Transient Recovery Voltage (TRV). One of the most severe TRV, normally, is found when the circuit breaker opens to eliminate a short circuit due to the high currents involved. The capability of the circuit breaker to withstand the overvoltage is expressed in terms of peak and rate of rise of the voltage (RRRV) [1], which shall be higher than those found during the electromagnetic transient studies.

Transient Recovery Voltage is one of the electromagnetic studies that shall be carried out at the final stage of an electrical system design. The study requires detailed information of the equipment used in the system. Normally, TRV studies are most found in the literature for high-voltage levels (> 15 kV systems) which are related to electrical power systems connected to the grid [2]-[8], nevertheless in offshore industrial power systems, which, normally, has the main voltage lower than 15 kV, they are much less common.

Regarding works which deal with transient voltage issues in industrial power systems, in [8] the influence of the circuit breaker model used is studied in a large industrial system.

In [9][10], issues due to TRV are investigated in 15 kV circuit-breakers which are installed in systems connected to step-up transformers. Works related to the mitigation measures of TRV in medium voltage systems with voltage up to 15 kV are also found in the literature. For example, in [11] the usage of ZnO devices is suggested to reduce the transient recovery voltage peaks. Furthermore, in [12] a 13.8 kV system is studied and solutions to mitigate the effects of the TRV are discussed.

Works related to transient recovery voltage in medium-voltage circuit breakers (from 1 kV to 30 kV) are not very common, especially for typical industrial secondary-voltage levels (e.g. 6.6 kV, 4.16 kV, 3.3 kV and 2.4 kV). In addition, the existent works which deal with industrial power systems do not investigate the influence of certain design parameters on the TRV results.

At initial phases of the industrial system design, TRV studies normally are not carried out and if a problem is found at a more advanced phase a solution must be addressed to mitigate the overvoltages.

Therefore, this work aims at verifying the main parameters that affect the TRV in an offshore industrial power system which operates isolated from the grid. Simulations are performed in a typical offshore installation and the effects in different voltage levels (13.8 kV and 4.16 kV) are analysed. The results are intended to give a first approximation of the main parameters that affect the TRV parameters (peak and RRRV) to be considered during the initial phases of the electrical system design.

II. System Modelling

The industrial power system under analysis is a typical offshore unit which is manly composed of large motors in the same voltage level of the main generators. The transient recovery voltages are analysed for the main two voltage levels, for instance, 13.8 kV and 4.16 kV. A scheme of the electrical system used in this paper is depicted in Fig. 1.

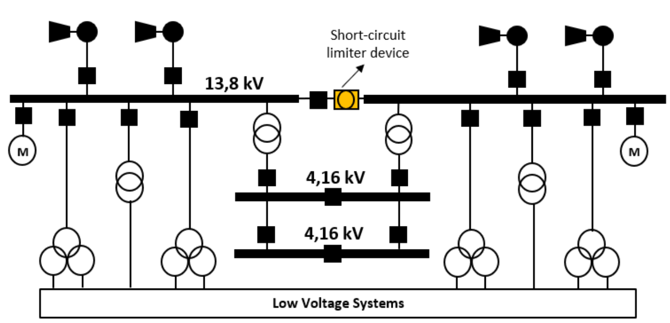

Fig. 1. Scheme of the electrical system under analysis.

As can be seen in the scheme, the electrical system is

R. S. Ferreira is with Petróleo Brasileiro S.A. - Petrobras, Brazil (e-mail: rodrigosousa@petrobras.com.br).

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composed of four main turbogenerators directly connected in the main switchgear, in 13.8 kV. The main panel is equipped with a short-circuit limiter device to keep the currents in the panels withstand levels. The limiter device operates faster than one cycle of the voltage after the short circuit has occurred, which indicates that when the circuit breaker actuates to eliminate the short circuit, the 13.8 kV main switchgear has already been split in two semi-bars.

The 4.16 kV voltage level are supplied by two-winding transformers and is composed of two panels. One panel is composed by electric motors and feeds the second 4.16 kV panel, which has only frequency converters connected.

The low-voltage level is supplied by many other transformers, but the detailed system is not presented in the scheme, because the TRV calculation focuses on the medium voltage system.

The simulations are performed in Alternative Transient Program (ATP) [13] and in the following subsections a quick explanation about the models used for each equipment is presented.

A. Generators

The choices of the models, especially for the rotating machines, shall consider that the electromagnetic transients persist for some microseconds. Therefore, the models can be substantially simpler than those used, for example, in electro-mechanical stability studies.

Each generator, for transient recovery voltage purposes, can be modelled by an ideal and constant voltage source behind the sub-transient impedance, that is, the sub-transient direct axis reactance $(x_d^{"})$ and stator resistance (r_s). This premise consider that the voltage regulator does not respond as fast as the electromagnetic transient occurs. Moreover, the rotor is completely neglected due to the higher time constants of the mechanical system when compared with the electrical ones. A scheme of the model used for each generator can be seen in Fig. 2. The internal voltage of the generator $(\dot{E}_{intG})$ can be calculated by Equation (1).

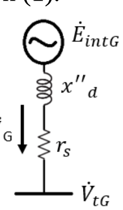

Fig. 2. Generator model.

$$\dot{E}_{intG} = \dot{V}_{tG} + (r_s + jx_d^{"}) \cdot \dot{I}_G \tag{1}$$

where $\dot{I}_G$ is the current through the generator stator windings.

Therefore, the internal voltage is calculated according to the demand being requested by the electrical loads. The parameters needed in the modelling are: sub-transient direct axis reactance, stator resistance and current flow.

B. Motors

Each motor is modelled in a similar way of the generators, which means that they are considered as ideal constant voltage sources behind the sub-transient impedance. The sub-transient impedance is calculated based on the X/R ratio and on the ratio between the locked rotor and rated currents. Therefore, parameters needed to model the motors are: locked rotor current, X/R relation and rated voltage.

C. Power Transformers

Power transformers are modelled by using the “Saturable Model” from ATP [13]. The main parameters of the model are based on the no-load and short-circuit tests and the saturation curve as well. As presented in Fig. 1 in the electrical system under consideration there are two and three-windings transformers, but the model is similar. The parameters used to model the transformers are: rated power, X/R relation, short-circuit impedance, saturation curve, connections and rated voltages.

D. Frequency Converters

The existent frequency converters in the system are non-regenerative type, hence they do not contribute for short-circuit. Moreover, they are equipped with shift transformers, hence the frequency converters have been modelled by static loads as constant impedance type, which is based on the electrical demand of each frequency converter.

E. Cables

To consider the high frequency phenomena, the cables have been considered according to the Clarke model in ATP [13], which takes the travelling wave characteristic into account. The main parameters are the per unit length resistance, inductance and capacitance and the length as well.

F. Circuit Breaker

The circuit breaker that opens during the simulation to eliminate the short circuit and which is also submitted to the transient recovery voltage, has been modelled by a “Models” device in ATP [13]. The model is like the ideal time-controlled switch which already exists in ATP, where the main input data are the chopping current and the opening and closure times. In addition, the model implemented generates the withstand curves (T100, T60, T30 and T10) as a function of the voltage class of the circuit breaker according to [1]. Moreover, the model also calculates the peak and maximum rate of rise of the recovery voltages (RRRV) considering the three phases.

G. Surge Capacitor and Stray Capacitances

Due to the high frequency characteristics of the transient recovery voltage, it is necessary to consider the capacitances involved in the circuit, which are due to the surge capacitors and the stray capacitances.

The surge capacitances are installed at the rotating machines terminal boxes aiming at reducing the overvoltages in the stator windings by increasing the rise time of an eventual transient surge that arrives at the machine line-end coils. The surge capacitors are chosen according to the rated voltage of the machine and for the voltage levels under consideration, the values are 0.25 μF and 0.5 μF, for 13.8 kV and 4.16 kV voltages, respectively [14][15].

In relation to the stray capacitances they refer to the insulation of the high voltage equipment. In the system the following considerations have been adopted:

- motors and generators: the stray capacitances were not considered, because they are much lower than the surge capacitors, hence they do not have relevant influence on the transient recovery voltages;
- power transformers: the stray capacitances have been considered between windings and from windings to ground, for all windings with rated voltage higher than 1 kV, which means that for low-voltage windings they are neglected. The values considered for the stray capacitances are in accordance with IEEE Std C37.011 [16];
- frequency converters: as previously informed the frequency converters of the system under analysis have a shift transformer with a high-voltage primary winding and a low-voltage secondary winding. Therefore, the stray capacitances of the primary winding have been considered according to premises adopted for the power transformers.

H. Surge Arresters

The high-voltage rotating machines of the system are equipped with surge arresters to mitigate the effects of the transient voltages in the windings. Therefore, the modelling includes these surge arresters by a non-linear resistor, which in ATP is introduced by the IxV curves (current as a function of voltage). For the simulations, typical curves for both voltage levels have been used.

I. Low-Voltage System

The remaining voltage levels of the electrical system do not have significant influence on the transient recovery voltages. Therefore, they have been modelled by static impedances representing constant loads connected directly on the secondary of the power transformers, which are calculated based on the electric power demand.

III. Simulation Results

To analyse the main parameters which affect the transient recovery voltage, many simulations has been performed by changing: generators' terminal voltage; number of motors and generators; surge capacitances of the motors; generators sub-transient reactance; motors locked rotor current and; the transformer short-circuit impedances. Firstly, the worst results of the original system (with the original parameters) have been found and the changes of the parameters are done in these worst conditions. The sensitivity analysis is performed in ATP Draw by changing the parameters studied in each case manually.

The main premises used to carry the simulations are summarized as follows:

- the TRV is calculated during the elimination of a three-phase ungrounded short circuit, which represents the worst condition for the overvoltages;
- when the circuit breaker starts to open the short-circuit is considered in steady state, due to the relay and circuit breaker processing times;
- the pre-fault voltage at generators terminals is considered as 1 pu;
- motors operate at no-load in order to achieve the highest internal voltages;
- the chopping current has been considered equal to 0 A, which is a conservative value and normally used in TRV studies.

Many simulations have been done to find the worst results in both system voltage levels, 13.8 kV and 4.16 kV. For this purpose, all possible short-circuit locations have been studied for different scenarios, which comprise maximum and minimum short-circuit results. The maximum short-circuit is used because under higher currents the TRV withstand envelop is lower. Moreover, the minimum short-circuit scenarios are also considered because they correspond to the system operating without the motor loads, which means that the capacitances of cables and surge capacitors are out of operation, therefore a higher RRRV is expected in these cases.

The worst results are showed in the next figures and the peak and rate of rise values of the voltage are also shown in TABLE I. For the 13.8 kV system the worst result is showed in Fig. 3, which has been obtained for the maximum short-circuit located at an outgoing to a motor load. For the 13.8 kV system the most severe result is related to the peak value, which requires a 24 kV circuit breaker or a 17 kV with higher capacities than those indicated in IEC 62271-100 [1], guaranteed by test reports.

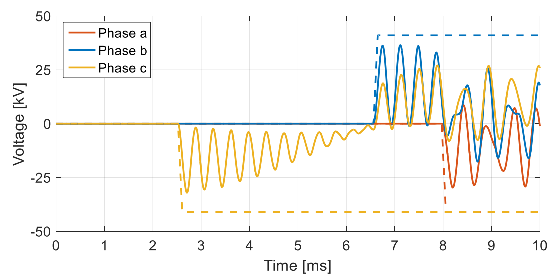

Fig. 3. Worst case for 13.8 kV system.

In relation to the 4.16 kV voltage system, according to Fig. 4 and TABLE I, a 12 kV circuit breaker is required to withstand the overvoltages, mainly because of the rate of rise of the overvoltages, which is a common issue when cleaning a secondary transformer fault [17]. Moreover, as can be seen in Fig. 5, the 12 kV circuit breaker is enough because for the short-circuit level under analysis it is possible to consider a T60 curve instead of the T100.

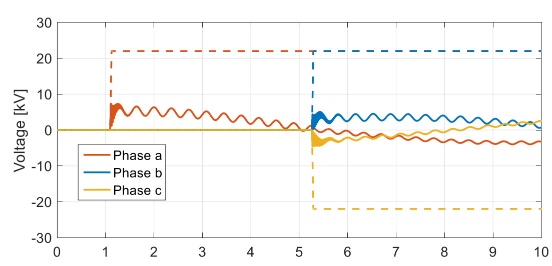

Fig. 4. Worst case for 4.16 kV system.

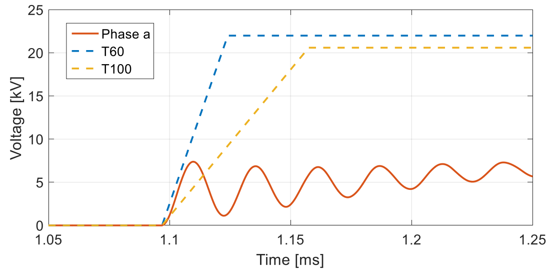

Fig. 5. Worst case for 4.16 kV system (T100 and T60).

TABLE I
WORST RESULTS FOR EACH VOLAGE LEVEL.

Voltage Level	Peak [kV]	RRRV [kV/µs]
13.8	36.5	0.219
4.16	7.4	0.660

In the next subsection the previous maximum results for the original system for both voltage levels, called in this paper as "base" case, are compared with those obtained by changing the parameters, one by time, to perform the sensitivity analysis. The waveforms are only presented for the phase which has presented the worst results, for instance, phase "b" for 13.8 kV system and phase "a" for 4.16 kV system. Moreover, the peak and rate of rise of the overvoltages are presented, which are also compared with the values obtained for the base case.

TABLE II presents the parameters studied, the variation used to perform the sensitivity analysis, and the reason to consider them. Basically, the parameters chosen are those which are defined during the initial phases of the electrical system design without considering their influences on the TRV results. The variation used is based on the typical values observed in the design of the system considered in this paper.

A. Case 1 - Generators Terminal Voltages

In this first case the transient recovery voltages are calculated by changing the generators terminals voltage. The values used are 0.95 and 1.05 pu in relation to the generator rated voltage (13.8 kV). The main results are presented in TABLE III and in Fig. 6 and in Fig. 7

According to the results it is possible to see that the TRV values (peak and RRRV) are directly proportional to the generator terminal voltages. Moreover, the variation of the values, which are in relation to the base case ones, are almost the same of the terminal voltage, that is, ±3%.

The main difference found between the results is the shift at the beginning of the overvoltages, observed only for the 4.16 kV system, which are related to the time that the current takes to crossing the zero, since a chopping current of 0 A has been considered.

TABLE III
RESULTS FOR CASE 1.

Sytem	Voltage [pu]	Peak [kV]	RRRV [kV/µs]	ΔPeak [% of Base]	ΔRRRV [% of Base]
13.8	1a) 0.95	35.4	0.213	-3.0	-2.7
	1b) 1.05	37.5	0.226	2.7	3.2
4.16	1a) 0.95	7.2	0.639	-2.7	-3.2
	1b) 1.05	7.6	0.679	2.7	2.9

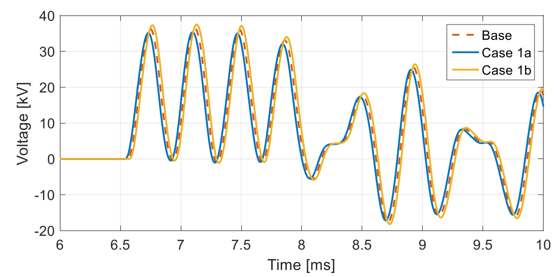

Fig. 6. Case 1 - 13.8 kV results.

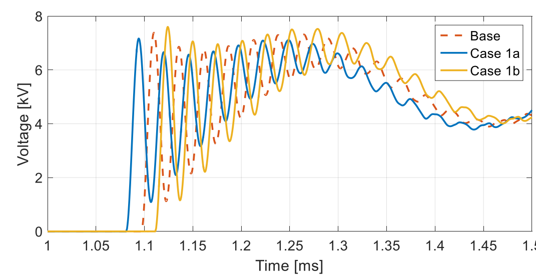

Fig. 7. Case 1 – 4.16 kV results.

B. Case 2 -Number of Motors

Other analysis performed is related to the number of motors in operation. This is an important case, because in an industrial system the number of motors is considerably higher than the number of generators and can vary depending on the project. For the 13.8 kV system the first simulation considers only the motor of the outgoing, in which the short circuit is being applied, in operation. In the second, half of the 13.8 kV

TABLE II
SUMMARY OF THE PARAMETERS STUDIED.

Case	Parameter	Variation	Reason
1	Generator Terminal Voltage	13.8 kV: 0.95 and 1.0 pu 4.16 kV: 0.95 and 1.0 pu	As the electrical offshore system operates isolated, it is normal that the voltage varies at the generation busbar. The variation used is related to typical values.
2	Number of Motors	13.8 kV: 1 and 4 4.16 kV: 1 and 19	The number of motors in operation can vary significantly in reason of the process plant need. The variation used covers the extreme possibilities.
3	Surge Capacitances	13.8 kV: 6 and none 4.16 kV: 5 and none	Standard surge capacitance values are normally used at the machine terminals; however, the capacitance could be optimized. The variation used covers the extreme possibilities.
4	Generators sub-transient reactance	13.8 kV: -30% e +30% 4.16 kV: -30% e +30%	Sub-transient reactance is chosen to keep the short-circuit within the acceptable limits. The variation used is related to typical values observed in different designs.
5	Number of Generators	13.8 kV: 1 e 3 4.16 kV: 1 e 3	The number of generators in operation depends on the electrical demand of the unity. The variation used cover the extreme possibilities.
6	Motor Locked Rotor Current	13.8 kV: -30% e +30% 4.16 kV: -30% e +30%	Motor locked rotor is defined do mitigate the effects of motor starting and short-circuit contribution. The variation used is related to typical values observed in different designs.
7	Transformers short-circuit impedance	13.8 kV: not applicable 4.16 kV: -30% e +30%	Transformers short-circuit impedances are defined to reduce the short-circuit in the lower voltage levels. The variation used is related to typical values observed in different designs.

motors are running. To clarify, in the base case simulation, all motors of 13.8 kV semi bar under analysis are in service.

In relation to the 4.16 kV, the simulations have been done considering all the motors out of service, and after all of them are put in operation. The results are presented in TABLE IV and in Fig. 8 and in Fig. 9. According to the simulations the results are different depending on the voltage level.

TABLE IV
RESULTS FOR CASE 2.

System	Motors in operation	Peak [kV]	RRRV [kV/μs]	ΔPeak [% of Base]	ΔRRRV [% of Base]
13.8	2a) Only 1	32.9	0.290	-9.9	32.4
	2b) 4	34.5	0.238	-5.5	8.7
4.16	2a) Only 1	6.5	0.602	-12.2	-8.8
	2b) 19	7.4	0.662	0.0	0.3

For the 13.8 kV system, the peak values are lower for lower number of motors in operation. Nevertheless, the rate of rise is higher for minor quantity of motors running, which is explained by the fact that when the motor is running the surge capacitors are also included, which reduce the rate of rise of the TRV. On the other hand, for the 4.16 kV system when all motors are off the peak and rate of rise of the overvoltages reduce. On the other hand, by switching on all motors, the influences were irrelevant.

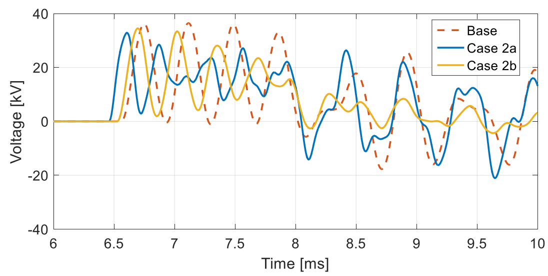

Fig. 8. Case 2 - 13.8 kV results.

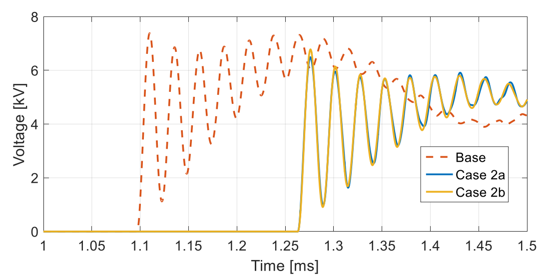

Fig. 9. Case 2 – 4.16 kV results.

C. Case 3 - Surge Capacitances

As explained before, surge capacitors are used to protect the turn insultation of the motors in case of a transient surge achieves the line-end coil. One of the disadvantages of this capacitors are the increasing of the capacitive ground-fault currents, which can be a concerning in high-resistance grounded systems. Therefore, to verify the influence of the surge capacitors, simulations are done with and without some of them. The methodology used was the same of the previous case, which means that for the 13.8 kV system, the first simulation considers only one surge capacitor and, in the second, none of them is operating. For the 4.16 kV system the simulations consider half and none of them, in each case.

The results for this case are presented in TABLE V and in Fig. 10 and Fig. 11.

TABLE V
RESULTS FOR CASE 3.

System	Surge Capacitors	Peak [kV]	RRV [kV/μs]	ΔPeak [% of Base]	ΔRRRV [% of Base]
13.8	3a) 6	35.0	0.220	-4.1	0.3
	3b) None	32.6	0.277	-10.7	26.5
4.16	3a) 5	7.4	0.667	0.0	1.1
	3b) None	7.8	0.675	5.4	2.3

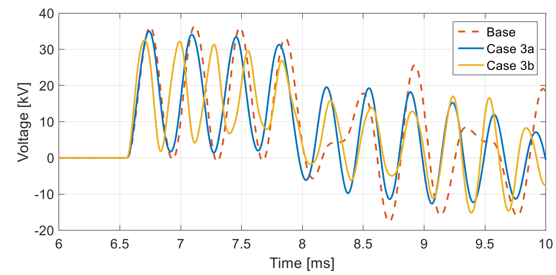

Fig. 10. Case 3 - 13.8 kV results.

Based on the results, for the 13.8 kV the amplitude always reduces, however, the rate of rise is significantly higher when all surge capacitors are neglected. For the 4.16 kV system, the amplitude only changes when all surge capacitors are disregarded. The rate of rise is always higher when the surge capacitances are not considered, nevertheless, the variations are much lower than the case 3b for the 13.8 kV system.

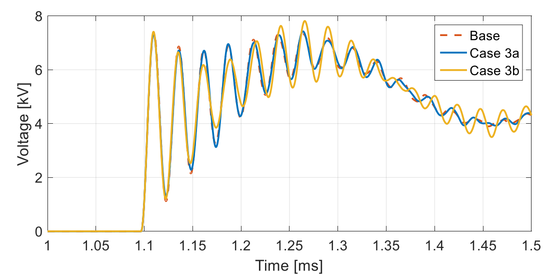

Fig. 11. Case 3 – 4.16 kV results.

D. Case 4 - Generators sub-transient reactance

In this item the influence of the sub-transient reactance, which is an important parameter used to control the short-circuit in the isolated electrical systems. Therefore, the simulations for both voltage levels, 13.8 kV and 4.16 kV, consider values with a variation of $\pm 30\%$ in relation to the base value. According to the results presented in TABLE VI and Fig. 12 and Fig. 13, for the 13.8 kV system, the peak values are always lower, independently of the variation of the sub-transient reactance, however the rate of rate has been found inversely proportional to the reactance.

TABLE VI
RESULTS FOR CASE 4.

System	x_d'' [pu]	Peak [kV]	RRRV [kV/μs]	ΔPeak [% of Base]	ΔRRRV [% of Base]
13.8	4a) -30%	33.4	0.233	-8.5	6.4
	4b) +30%	34.2	0.195	-3.8	-8.7
4.16	4a) -30%	7.7	0.692	4.1	4.8
	4b) +30%	7.4	0.634	0.0	-3.9

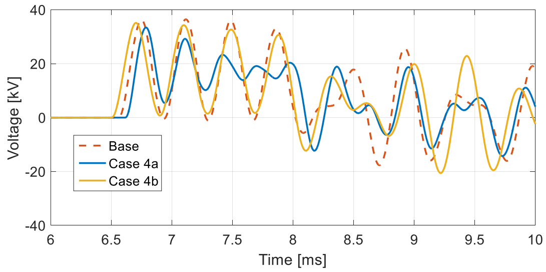

Fig. 12. Case 4 - 13.8 kV results.

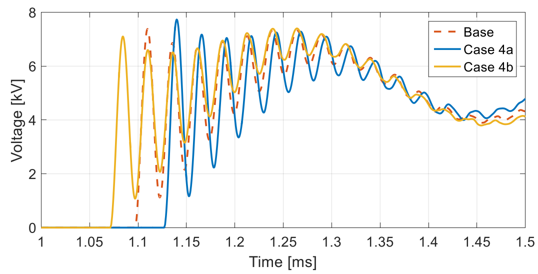

Fig. 13. Case 4 – 4.16 kV results.

For the 4.16 kV system, the variations are lower than in 13.8kV system, and the results get worse for lower values of generator sub-transient reactance.

E. Case 5 - Number of Generators

The base cases consider two main generators in operation in the semi-bar which represents the worst case in 13.8 kV system and four for the 4.16 kV system. Therefore, to verify the influence of the number of generators on the transient recovery voltage, simulations are done by changing to one generator in 13.8 kV and to three for 4.16 kV. In fact, in the 13.8 kV system the total number of generators remains the same, nevertheless one generator from the side which presented the worst TRV are switched off and the generator of the other semi bar is turned on. The results are presented in TABLE VII and in Fig. 14 and in Fig. 15.

TABLE VII
RESULTS FOR CASE 5.

Voltage Level	Number of Generators	Peak [kV]	RRV [kV/μs]	ΔPeak [% of Base]	ΔRRRV [% of Base]
13.8	5a) 1	32.4	0.172	-11.2	-21.5
4.16	5a) 3	7.3	0.618	-1.4	-6.4

According to the values and waveforms, the number of generators in operation has great influence on the TRV results, especially for the 13.8 kV system, which presented variations more than 10% and 20% for the peak and rate of rise, respectively. In the 4.16 kV system, the variation was lower, even though a reduction of more than 6% has been found for the rate of rise.

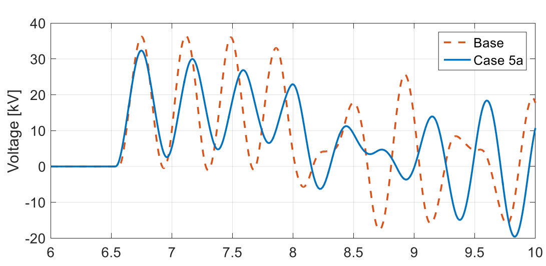

Fig. 14. Case 5 - 13.8 kV results.

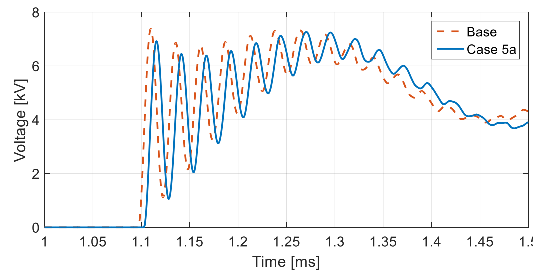

Fig. 15. Case 5 – 4.16 kV results.

F. Case 6 - Motor locked current

This item aims to verify the influence of the motor locked current ratio (ration between the locked rotor and rated currents) on the TRV results. The motor current ratio, normally, is an important parameter defined do mitigate the effects of motor starting and short-circuit. Therefore, simulations were done in 13.8 kV system by changing in ±30% the locked rotor current, in relation to the base value, only for the motor related to the outgoing which the worst TRV has been achieved. Nevertheless, for the 4.16 kV system, the locked rotor current ratio has been changed for all motors connected in that system. According to the values presented in TABLE VIII and waveforms showed in Fig. 16 and Fig. 17 a directly proportional influence were found only in 13.8 kV system, since no variation was found in the 4.16 kV for both, peak and rate of rise results, even changing the values of all motors.

TABLE VIII
RESULTS FOR CASE 6.

Voltage Level	Ip/In [pu]	Peak [kV]	RRV [kV/μs]	ΔPeak [% of Base]	ΔRRRV [% of Base]
13.8	6a) -30%	37.2	0.221	1.9	0.9
	6b) +30%	34.4	0.212	-5.8	-3.2
4.16	6a) -30%	7.4	0.660	0.0	0.0
	6b) +30%	7.4	0.660	0.0	0.0

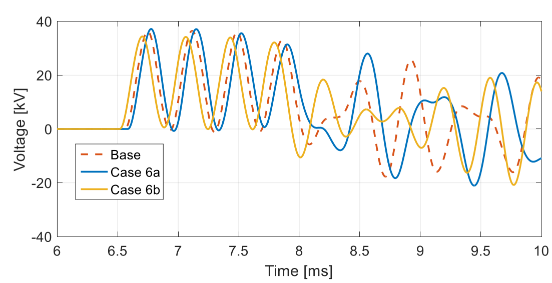

Fig. 16. Case 6 - 13.8 kV results.

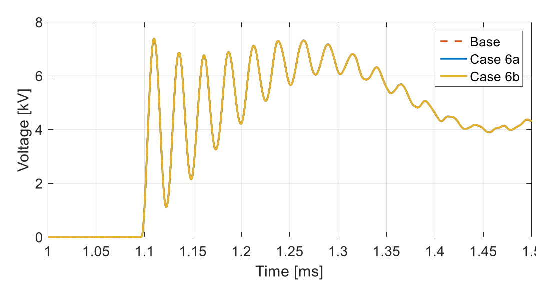

Fig. 17. Case 1 – 4.16 kV results.

The variations found in the 13.8 kV system were relevant, especially for the increasing of he locked current ratio, which presented a reduction of about 6% and 3% in the peak and rate of rise, respectively. Moreover, a undirect proportionality has been found between the locked rotor and TRV values.

G. Case 7 - Transformer short-circuit impedance

This item verifies the influence of the transformer short-circuit impedance on the transient recovery voltages. The analysis is done only for the 4.16 kV system, since there is no transformer between the generators and 13.8 kV system, which means that no influence is expected by changing the impedance of a 13.8 kV-4.16kV on the TRVs found in the 13.8 kV system.

The results found for the 4.16 kV system, which were obtained by changing the base impedance by ±30% are presented in TABLE IX and in Fig. 18.

TABLE IX
RESULTS FOR CASE 7.

System	*Z*	Peak [kV]	RRV [kV/μs]	ΔPeak [% of Base]	ΔRRRV [% of Base]
4.16	7a) -30%	7.7	0.736	4.1	11.5
	7b) +30%	8.1	0.591	9.5	-10.5

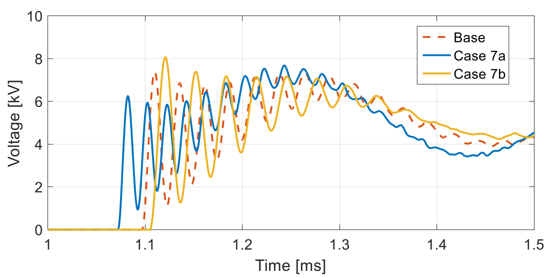

Fig. 18. Case 7 – 4.16 kV results.

Based on the results, the TRV are very sensible to the transformer short-circuit impedance. The amplitude was found always higher than that obtained in the base case. Moreover, higher impedance lead to a lower rate of rise.

IV. CONCLUSIONS

In this paper the influence of some parameters on the transient recovery voltage has been verified. Simulations have been performed in a typical offshore industrial system by changing some design parameters, for instance, generators internal voltage and sub-transient reactance, number of motors and generators, surge capacitors, motors locked-rotor current and transformer short-circuit impedance, which have been analysed for the main voltage level of the unit, 13.8 kV, and a secondary voltage level (4.16 kV). The main objective is to know, at initial design phases, the parameters that can affect the TRV, which is verified only at the final phases of the electrical system design. According to the results, almost all parameters studied have influence on the results, which main variations are listed below in decrescent order:

13.8 kV system - peak: number of generators and motors in operation and sub-transient reactance; rate of rise: number of generators and motors, generator sub-transient reactance and surge capacitances.

4.16 kV system - peak: number of motors, generator sub-transient reactance and transformer short-circuit impedance; rate of rise: transformer short-circuit impedance and number of motors and generators.

Using the results of this paper, if the parameters which have more influence on the TRV results change from one design to the other, the impacts on the electrical system can be mitigated in sooner phases of the electrical system design. Therefore, the choices made during the initial phases of the design (such as electrical system topology, equipment parameters, etc) can also take their effects on the TRV results account before the TRV study be performed.

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