Modeling Three-Phase Short-Circuits for Radial Distribution Systems

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Abstract - **Monitoring radial distribution systems in short-circuit conditions represents a quite important issue of electric power networks supplied by renewable sources. The method presented in the paper aims to establish in laboratory conditions, using the similitude criteria, the real value and the duration of a three phase short-circuit current acting in renewable sources connected to the electric grids. Since, due to the high values of the short-circuit currents it is difficult to test the operation of the relays in situ, for instance in transformer stations or substations, it is mandatory to test and set using the injection of secondary currents. Consequently, the paper presents the modeling of a real grid, in order to emulate, as accurate as possible. The results of the measurements, reported to the real grid, represent the real ones, existing at the three phase short-circuit level. Therefore, even from the early phase of design, one may choose the breaking equipment, capable to face the conditions of dynamic and thermal stability. Since the reporting factors are known, along with the possibility of using the accurate reported value of the real short-circuit current on the model, the tests on model present advantages in relation to the use of the devices of secondary currents injection. The results of the measurements on the model confirm the viability of the last testing method here depicted.**

Cuvinte cheie: *surse de energie regenerabile,criteriu de similitudine, scurtcircuit, injecție de curent, modelul liniei electrice.*

Keywords: *renewable energy sources, similitude criteria, short circuit, current injection, electric transmission line model.*

INTRODUCTION

The connection of the renewable sources to power systems is achieved using overhead or cable transmission lines. Short-circuit conditions appear when a low value of the impedance links two points having different electric potentials [1]. If the short-circuit occurs far from the sources, the limitation of the short-circuit current is achieved by the short-circuit equivalent impedance of the grid. At the source, the stator reaction to short-circuit is reduced, consequently the voltage remains practically the same as before the fault occurrence [1].

The most frequent causes of short-circuits are:

- the decrease of the impedance due to the deterioration of the insulation;
- contact of two-line conductors without or with contact to the earth;
- contact of three-line conductors without or with contact to the earth;
- faulty maneuvers during operation.

SHORT CIRCUIT CURRENT LIMITATION IN RADIAL NETWORKS

Radial distribution systems for electric power, common in Europe and USA, normally use protective relays for coordinating protection against faults. However, the growing interest in distributed power production poses a problem for the distributed generation of electricity because the system will lose its radial nature, disrupting the coordination of protective relays. Using a fault current limiter that minimizes in a radial network the effect of distributed generation on power system relay protection coordination could be a solution to this problem. Fault current limiter improves the goal to simulate the usual appearance of stability and limits the transient voltage recovery in distributed systems. Fault current limiters have been developed starting from the hybrid static and electromechanical switching variants.

Most distribution systems in North America are operating in radial configuration, predominantly due to the simplicity of the operation and the reduced fault currents determined by overcurrent protection. These two advantages are due to the fact that in radial systems, on any line, power flows only in one direction.

In these distribution systems, the protective equipment should only detect current without having to detect direction. Usually inverse-time-overcurrent-relays [2] are used for relays coordination. Introduction of coordination relays ensures safe and redundant protection schemes, minimizing at the same time the disturbances at the end users level.

Distributed power systems are defined as a power source connected directly to the distribution network of a power system. It is estimated that by 2015, 20-30% of all installed power generators will be ranked in the category of distributed sources of electricity.

With the introduction of distributed systems in radial distribution systems, the nature of radial power flow is not determined. Depending on load conditions, it may not be possible the reconnection of protective relays. It is well known that protective devices in a multisource system must be dependent of flow direction and fault relays must be coordinated, because the current can flow in both directions. Even if the load is such that the current will flow only in one direction, distributed systems can reduce the action range of the relays, disturbing their coordination. Another problem arising from the introduction of distributed systems is the increased level of faulty currents, which pose problems to the inverse time overcurrent relays, which are coordinated based on presumed fault current.

Several ideas were introduced as possible solutions for the protection by overcurrent relays in distributed systems, including digital relays with fast reconnection based on microprocessor and adapted protection. Although these solutions are adequate from a technical standpoint, they involve high initial costs of equipment to replace the existing relays by relays based on microprocessor, special switching devices and computers to coordinate the switching devices control.

Moreover, the technical complexity of these solutions includes the need to change the setting curves of the relays, when a distributed system is removed from service or put into operation. Also, it must ensure the security of communication lines between station computers and protection relays. Due to these complications and the high cost, these solutions are not viable for current distributed systems.

Most proposed solutions to the problem outlined above involve the modification of the existing protection schemes in order to adapt them to the requirements of distributed systems. The implementation of such solutions tend to be expensive, due to the prices of the equipment, which reduce the benefit of distributed systems integration in energy systems. An alternative approach would be to minimize the contribution of distributed systems during a fault, without taking into account the negative effects on the network or, in other words, considering that the network works without faults.

A possible solution is to implement a fault current limiter that limits the current through the distributed network during a fault. Otherwise it would be a free power flow from the distributed grid to the power system. The advantage of this solution is that it is not necessary to replace the existing protection relays in the distribution systems.

Before taking into account the current technologies meant to limit the fault current contribution in distributed systems must first be determined operating conditions and characteristics of such a limiter.

EFFECTS OF SHORT-CIRCUITS

The consequences of short-circuits depend on the type, the duration and the location of the fault and the value of the current, being determined by [3]:

- the power of the wind renewable sources supplying the short-circuit;
- the distance between the wind renewable sources and the fault location, which in turn depends on the equivalent short-circuit impedance;
- the duration between the short-circuit occurrence and the isolation of the fault location;
- the type of the short-circuit, namely mono, bi or three phases short-circuit.

The consequences of short-circuits are:

- at the fault location short circuits are due to the occurrence of an electric arc, the destruction of the isolation of conductors which are the consequence of a high value of the current density;
- in the transmission line that supplies the short-circuit, important voltage drop occurs, perturbing the normal operation of customers and the faulty element could be destroyed due to the decrease of the resistance of the isolation. The commutation equipment, having the role to isolate the fault location crossed by the short-circuit current is very stressed by the thermal and dynamic effects of the short-circuit current and in some cases, it becomes definitively damaged. In circuits belonging to the adjacent grids, the voltage drops, and dynamic instabilities occur too.

The connection of renewable sources to the power system can be achieved in normal operation or in short-circuit conditions. In the last case it is important to be aware of:

- the waveform of the short-circuit current and the physic model of the short-circuited grid;
- the parameters of the circuit that limits the short-circuit current;
- the dependence of the current on the type of the short-circuit and the possibilities of computation of the component of permanent regime.

The analytic computational relations are based on the following hypothesis [4], [5]:

- the overhead transmission lines are considered by their longitudinal resistance and reactance, the transversal admittance being neglected; this leads to a sub evaluation of the short-circuit power;
- the resistance of the transformers and of the electric machines are neglected, due to the inductive character of these equipment;
- in the cases of asymmetric short-circuits, the direct and inverse sequence reactance are considered equals, which leads as well to a sub evaluation of the short-circuit power;
- the components of the grid are considered to be balanced and the electromotive forces of the wind turbines that supply the short-circuit have the same RMS values and initial phases; consequently, they exhibit only the direct component;
- the circuits are considered linear, with lumped parameters; therefore, the principle of superposition and the representation of the sub grids by equivalent impedances is applicable;
- the occurrence of the electric arc in the short-circuit location can be also in some cases neglected, considering consequently a firm short-circuit.

CRITERIA OF SIMILITUDE

The structure of a renewable sources grid is quite complex, including numerous equipment as:

- generators;
- power transformers;
- transmission lines operating at different voltages, etc.

The dielectric stress at the recovery oscillating voltage depends on the structure of the grid. A fast solution to determine the oscillating voltage consists in modeling the short-circuit processes [6]. Modeling consists in reproducing the short-circuit processes that occur in high voltage grids at a reduce scale in a so-called reported grid based on similitude criteria. The values defined for the high voltage grid and for the model grid are as follows:

For the high voltage grid:

- the reported voltage: U_r ;
- the reported current: I_r ;
- the reported power: $P_r = U_r \cdot I_r$;
- the reported impedance: $Z_r = U_r^2 / S_r$;
- the reported admittance: $Y_r = 1 / Z_r$.

while for the model grid:

- the base voltage: U_m;
- the base current: I_m;
- the base power: $P_m = U_m \cdot I_m$;
- the base impedance: $Z_m = U_m^2 / S_m$;
- the base admittance: $Y_m = 1 / Z_m$.

The first criterion of similitude is the criterion of the conservation of the rms value and of the phase of the impedance, the dependencies being as follows:

$$\begin{cases} R_m = \dfrac{Z_m}{Z_r} \cdot R_r \\ L_m = \dfrac{\omega_r}{\omega_m} \cdot \dfrac{Z_m}{Z_r} \cdot L_r \\ C_m = \dfrac{\omega_r}{\omega_m} \cdot \dfrac{Z_m}{Z_r} \cdot C_r \end{cases} \tag{1}$$

The second criterion of similitude is the criterion of the conservation of the oscillation factor. The condition is:

$$1 + e^{-\delta_r \frac{\pi}{\omega_{er}}} = 1 + e^{-\delta_m \frac{\pi}{\omega_{em}}} \tag{2}$$

The self-pulsation of the high voltage grid, ω_{er} and the self-pulsation of the model grid, ω_{em} are defined by the following relations:

$$\begin{cases} \omega_{er}^2 = \omega_{0r}^2 - \delta_r^2 \\ \omega_{em}^2 = \omega_{0m}^2 - \delta_m^2 \end{cases} \tag{3}$$

$$\delta_m = \delta_r \frac{\omega_m}{\omega_r} \tag{4}$$

$$\omega_{em} = \omega_{er} \frac{\omega_m}{\omega_r} \tag{5}$$

Compliance with the conditions of equations (4) and (5) regarding the damping and the self-pulsation lead to the conservation of the oscillation factor.

The model can also be miniaturized, because it is possible that the frequency of the model may differ from the frequency of the grid and of the other components of the model, like reduced scale inductors and capacitors. However, in practice, the frequency of the models is the same as the frequency of the high voltage grid [7], [8].

Next, a single-phase model of a three-phase commutation process is presented. Fig. 1 depicts the three-phase grid with a power breaker disconnecting a shortcircuit.

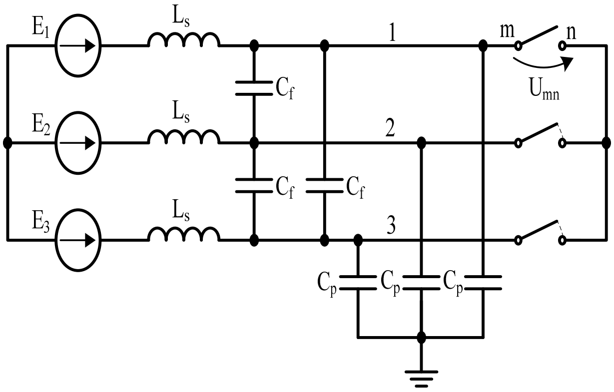

Fig. 1. The principle circuit of a three-phase grid at the disconnection of a three-phase short-circuit.

The electric arc assures the continuity of the circuit. In the moment in which the current crosses zero in phase one, the phase gets interrupted. However, phases two and three continue to be in conduction, due to the electric arc and the equivalent circuit that depicts the oscillatory process having the pulsation ω_0 has to be considered. The voltage at the industrial frequency in phase one, can be obtained from the equivalent circuit depicted in Fig. 2.

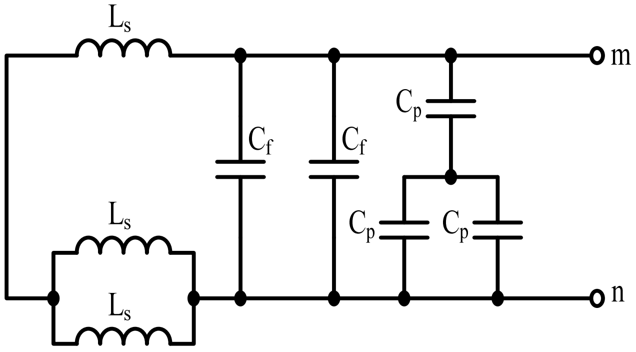

Fig. 2. The equivalent for the oscillatory process.

The electric pulsation is defined by the equation:

$$\omega_0 = \sqrt{\frac{1}{L_s C_s}} \tag{6}$$

where:

- L_s represents the operational inductance defined by the relation: $L_s = (2/3) \cdot L_r$; in which L_r – is the total inductance;

- C_s represents an operational capacity defined by the relation: $C_s = 3C_f + C_p$.

The instantaneous voltage of industrial frequency at the input stage of the circuit is determined by the relation:

$$U_{mn} = e_1 - e_2 = 1{,}5\sqrt{2}E \tag{7}$$

Consequently, the interruption of the phase one of the three phase grid can be modeled as a single-phase circuit, like in Fig. 3.

For a simpler grid, the single-phase modeling of the commutation process from three phase grids, can be achieved using the symmetrical components theory.

In the following, is presented the structure of a model, in which one can observe the power sources, the transmission lines, the power transformers, the limiting inductors, the loads and the breaker.

The power sources are modeled in compliance with Fig. 3.

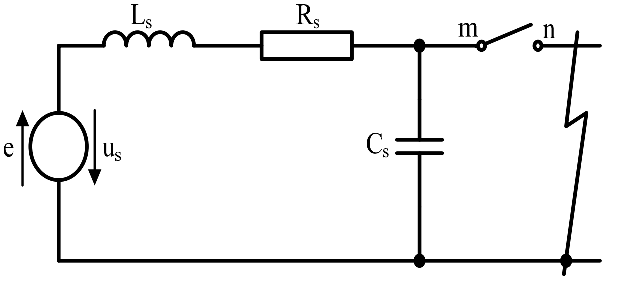

Fig. 3. The equivalent scheme depicting the single-phase interruption process.

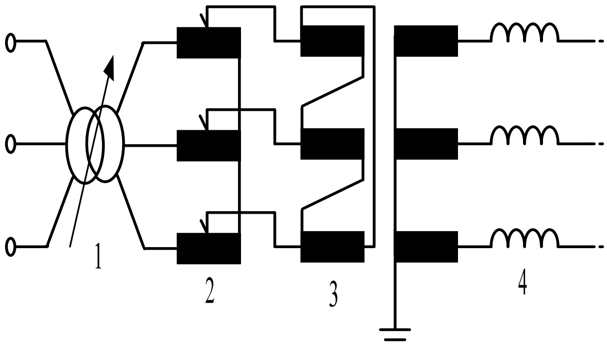

Fig. 4. The equivalent circuit of a power source.

In Fig. 4, one can distinguish the following items:

1) phase regulator

2) autotransformer,

3) high-power single-phase transformers having a unitary transforming ratio (220/220V) and minimum dispersion

4) *X*, the sub-synchronous reactance of the generator.

For a single-phase modeling, the transmission lines are modeled by at least six Π or Γ quadrupoles.

The equivalent circuit of the transmission line is presented in Fig. 5.

The transformer and the current limiting inductor are also modeled as quadrupoles.

The load is modeled by an ensemble of resistors, capacities and inductances parallel connected.

The modeling of the breaker is achieved considering a few requirements:

- in the position OFF, the resistance of the breaker is infinite;
- in the position ON, the resistance of the breaker is zero.

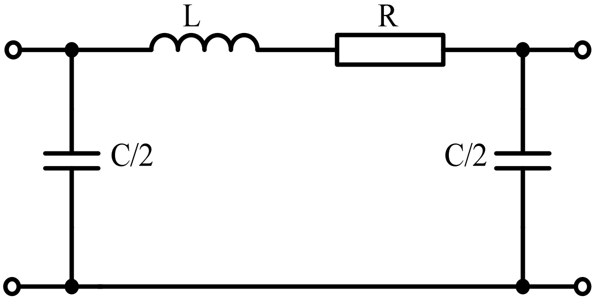

Fig. 5. The equivalent circuit of a transmission line.

EXPERIMENTAL MODEL

The laboratory setup meant for short-circuit modelling is presented in Fig. 6. The source which supplies the transmission line is modeled using an ensemble motor-generator being radially connected to an inductive load, having the drawn current adjustable in steps. In the area that supply the load a three-phase fault is simulated. The selectivity of the protection and the electric values that occurs during the fault are computed.

The model presents the following facilities:

- the parallel connection of two generators along with the check of synchronism conditions through their synchronizing mode;
- the parallel or in loop connection of two radial loads;
- recording the rated and of the fault values in the simulation process, using the “Three phase energy analyzer – STAR 3”.

In order that the model fulfills the functions of a renewable energy source connected to the energy system, it is compulsory to implement the specific protections. In the case of the generator these types of protections are:

- Maximal instantaneous current protection;
- Delayed maximal current protection;
- Maximal voltage protection;
- Minimal voltage protection;
- Frequency protection.

while in the case of the consumer they are:

- Maximal instantaneous current protection;
- Maximal instantaneous current protection.

The reporting process of the transformation from absolute values into reported values consists in using the relations presented in section IV, referring to the similitude criteria.

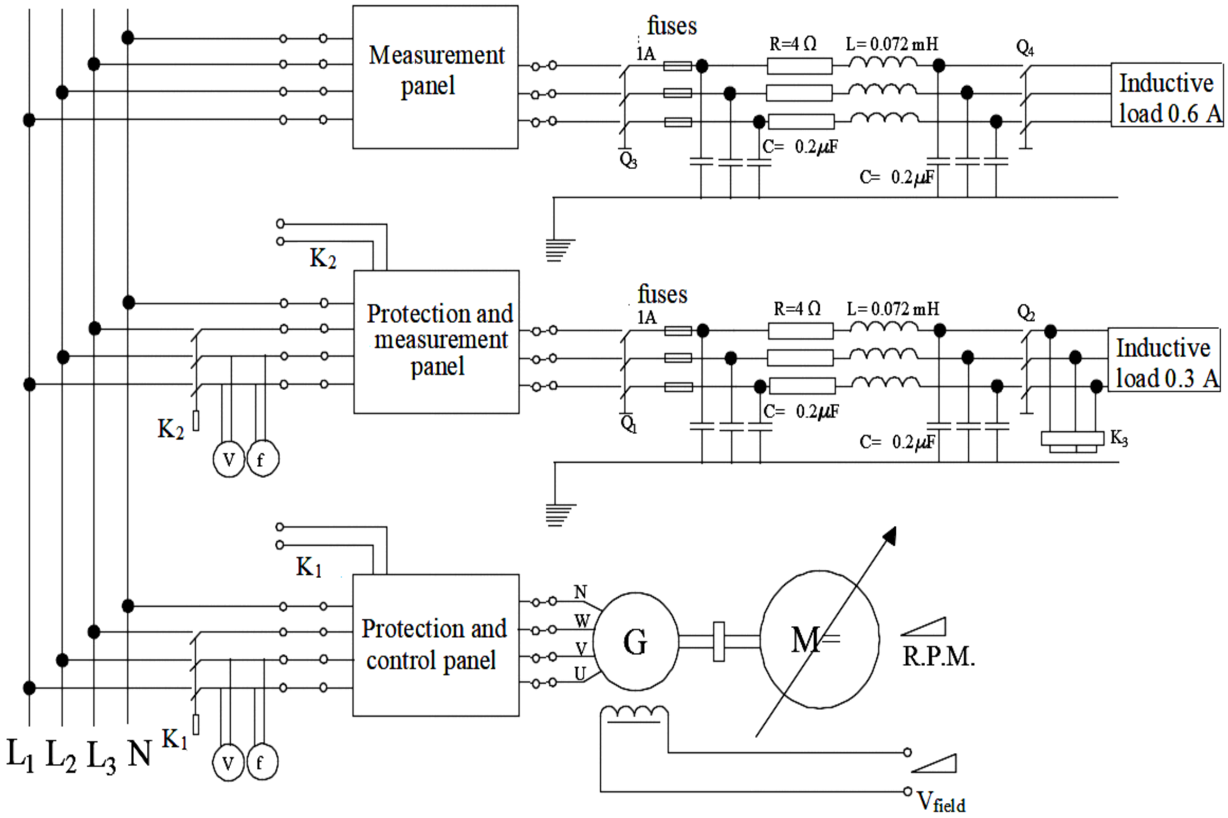

Fig. 6. The scheme of the modelled grid.

Experimental Results Obtained on the Model

To determine the three-phase short-circuit current in the modelled grid in Fig. 6, means to go through the following steps:

- Step 1: Connect the generator and using the control panel set the speed of the generator and the field voltage until the rated values are obtained, namely $V = 400$ V and until the rated values are obtained, namely $V = 400$ V and $f = 50$ hz.
- Step 2: Connect line one, which in a normal operation regime, with the breakers Q_1 and Q_2 connected, draws a current $I = 0.3$ A; in the moment of the connection of the consumer one in this line the voltage drops from $V = 400$ V, to $V' = 390$ V, but using the field control, the value is reestablished to the initial set value V of 400 V.
- Step 3: Finally, connect line two. Line two supplies a consumer which in normal operation draws a current of 0.6 A through the breakers Q_3 and Q_4. In the moment of the connection of the consumer the voltage drops from

400 V, to 370 V and the field voltage restore the voltage to the initial value of 400 V.

Table I depicts the results of the measurements in line one on the model and in Table II the values that result in the real scheme. These values are obtained from the conversion from reported values in absolute values.

At the moment $t = 4$ sec. a three-phase fault appears in Fig. 7 and Fig. 8. The faulty current is $I_k = 1.5$ kA. In the moment of the occurrence of the fault, the maximal delayed current protection acts, having a current set to $I_{max\text{II}} = 0.8$ A and a delay of t = 0.8 sec. and after another 0.8 sec., line one acts with an impulse to the contactor K_2.

The generator continues to supply line two, without fault, at a power of 413 VA and a current of 0.6 A. In the moment of a fault occurrence until its cancellation, the voltage drops from 400 V to 377 V.

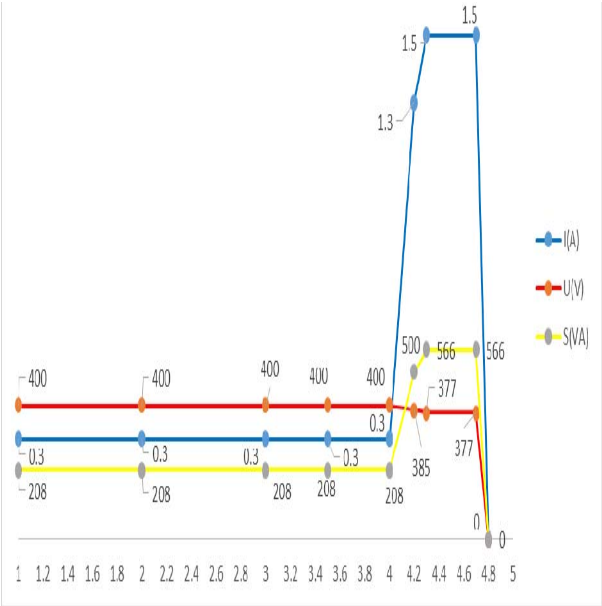

Fig. 7. Three phase short-circuit at the end of line one, 0.4 kV.

TABLE I.

ELECTRIC VALUES MEASURED OF THE MODEL OF LINE ONE

		0,4 kV		
t (s)	*I* (A)	V_f (V)	V_l (V)	*S* (VA)
1	0,3	230	400	208
2	0,3	230	400	208
3	0,3	230	400	208
4	0,3	230	400	208
4,2	1,3	222	385	500
4,4	1,5	218	377	566
4,7	1,5	218	377	566
4,8	0	0	0	0

In order to model the three-phase short-circuit in line one, one must connect the contactor K_3 (Fig. 6).

TABLE II.

REAL REPORTED ELECTRIC VALUES IN LINE ONE

		20 kV		
t (s)	*I* (A)	*I* (A)	*V* (kV)	*S* (MVA)
1	0,3	86	20	3
2	0,3	86	20	3
3	0,3	86	20	3
4	0,3	86	20	3
4,2	1,3	374	19,25	12,47
4,4	1,5	432	18,85	13,66
4,7	1,5	432	18,85	13,66
4,8	0	0	0	0

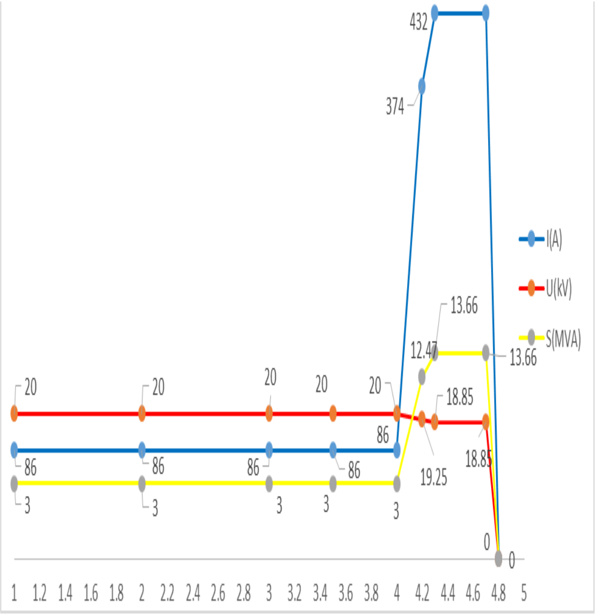

Fig. 8. The values of the three-phase short circuit current reported to the modeled grid in line one.

The measured values on the model are reported to the real grid, resulting the following faulty real values: I_k = 432 A, V_k =18.85 kV and S_k =13.66 MVA, according to Table II.

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From Fig. 9 one may observe that until the moment in which de fault occurs, the generator supplies the model with the power of 624 VA, which means 9 MVA on the modeled grid. The power drawn by the two consumers in line one is of 208 VA, respectively 413 VA on the model and 3 MVA, respectively of 6 MVA in the grid.

In the moment in which the fault occurs, namely at the moment t = 4 sec., the current increases to the value of 2.1 A, while the voltage drops to the value of 380 V; meanwhile the apparent power has the value of 1382 VA. After the disconnection of the line through the maximal delayed current protection, the values recorded on the measuring module of the control panel of the generator are I = 0.6 A, V= 410 V, S = 413 VA. In this status of the model, the voltage is set again to the value of 400 V, using the field control voltage.

The values measured on the control panel of the generator are reported to the grid voltage of 20 kV. The values determined on the real grid during the fault are: I_k = 605 A, V_k = 19 kV, S_k = 19.91 MVA, respectively after the clearing of the fault: *I* = 173A, *V* = 20 kV and *S* = 6.14 MVA.

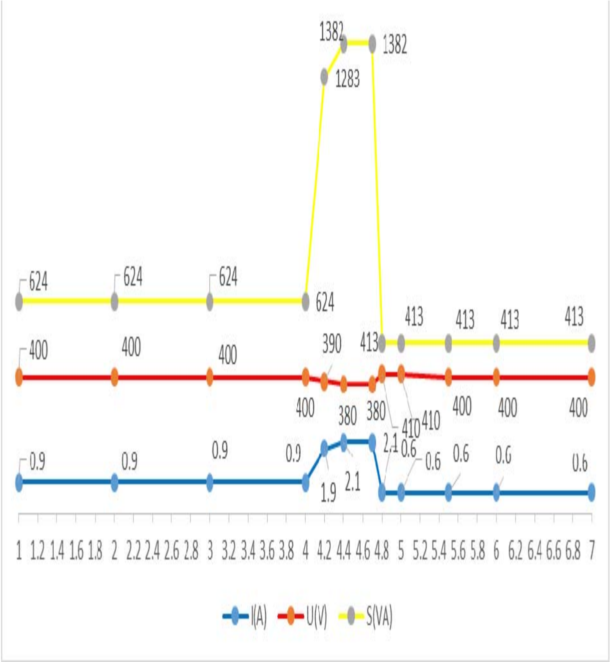

Fig. 9. Three phase circuit at the end of line one; recorded values on the generator.

CONCLUSIONS

The analysis of the three-phase circuit on model in the laboratory [9], highlights the practical advantages of the adopted solution, as follows:

- in the case of faults on overhead transmission lines that supply consumers one and two, the appropriate operation of the protections is important, the faults being cancelled by the protections themselves, the wind turbine continuing to operate;
- in the case of faults on the main line in which the renewable source is injecting power, if the faults duration overcomes 50 ms, the wind turbine disconnects due to the minimal voltage protection;
- the newly renewable source commissioned in the farms can be also connected if all the protection measures are provided; protection measures must not affect the consumers supply in case of local short circuits;

- even if there are no faults in the gird in which the renewable source injects power, it is possible that in the lack of a static compensation measure, the minimal voltage protection operates.

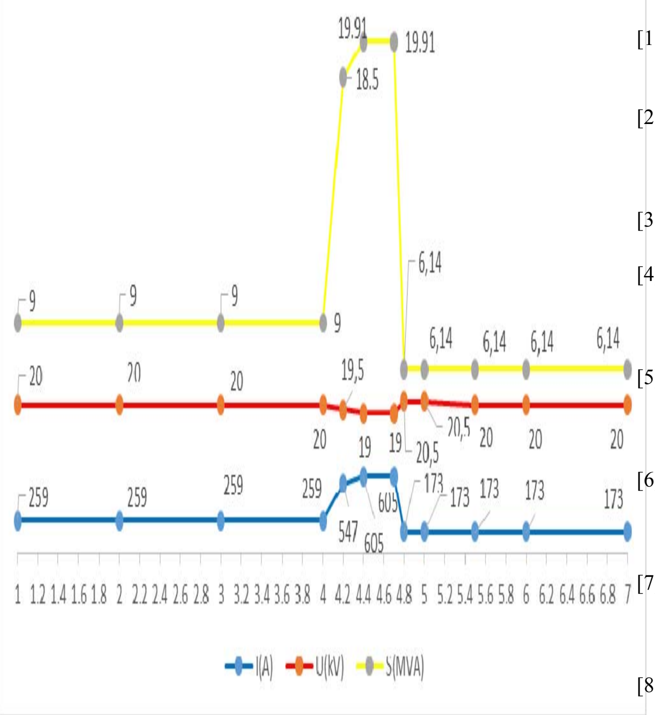

Fig. 10. The values of the three-phase short circuit current on the generator, reported to the modeled grid line one.

In the future, the authors propose to study the influence of variable wind velocity on the short-circuit mode generated by wind turbines [10].

The presented paper highlights the practical advantage of laboratory testing of medium and high voltage equipment, compared to the theoretical analysis done by simulation [11, 12, 13].

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