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Distance Protections in the Power System Lines with Connected Wind Farms

Adrian Halinka and Michał Szewczyk
Silesian University of Technology
Poland

1. Introduction

In recent years there has been an intensive effort to increase the participation of renewable sources of electricity in the fuel and energy balance of many countries. In particular, this relates to the power of wind farms (WF) attached to the power system at both the distribution network (the level of MV and 110 kV) and the HV transmission network (220 kV and 400 kV)¹. The number and the level of power (from a dozen to about 100 MW) of wind farms attached to the power system are growing steadily, increasing the participation and the role of such sources in the overall energy balance. Incorporating renewable energy sources into the power system entails a number of new challenges for the power system protections in that it will have an impact on distance protections which use the impedance criteria as the basis for decision-making. The prevalence of distance protections in the distribution networks of 110 kV and transmission networks necessitates an analysis of their functioning in the new conditions. This study will be considering selected factors which influence the proper functioning of distance protections in the distribution networks with the wind farms connected to the power system.

2. Interaction of dispersed power generation sources (DPGS) with the power grid

There are two main elements determining the character of work of the so-called dispersed generation objects with the power grid. They are the type of the generator and the way of connection.

In the case of using asynchronous generators, only parallel “cooperation” with the power system is possible. This is due to the fact that reactive power is taken from the system for magnetization. When the synchronous generator is used or the generator is connected by the power converter, both parallel or autonomous (in the power island) work is possible.

The level of generating power and the quality of energy have to be taken into consideration when dispersed power sources are to be connected to the distribution network. In regard to wind farms, it should be emphasized that they are mainly connected to the HV distribution

¹ The way of connection and power grid configuration differs in many countries. Sample configurations are taken from the Polish Power Grid but can be easily adapted to the specific conditions in the particular countries.

network for the reason of their relatively high generating power and not the best quality of energy. This connection is usually made by the HV to MV transformer. It couples an internal wind farm electrical network (on the MV level) with the HV distribution network. The internal wind farm network consists of cable MV lines working in the trunk configuration connecting individual wind turbines with the coupling HV/MV transformer. Fig. 1 shows a sample structure of the internal wind farm network.

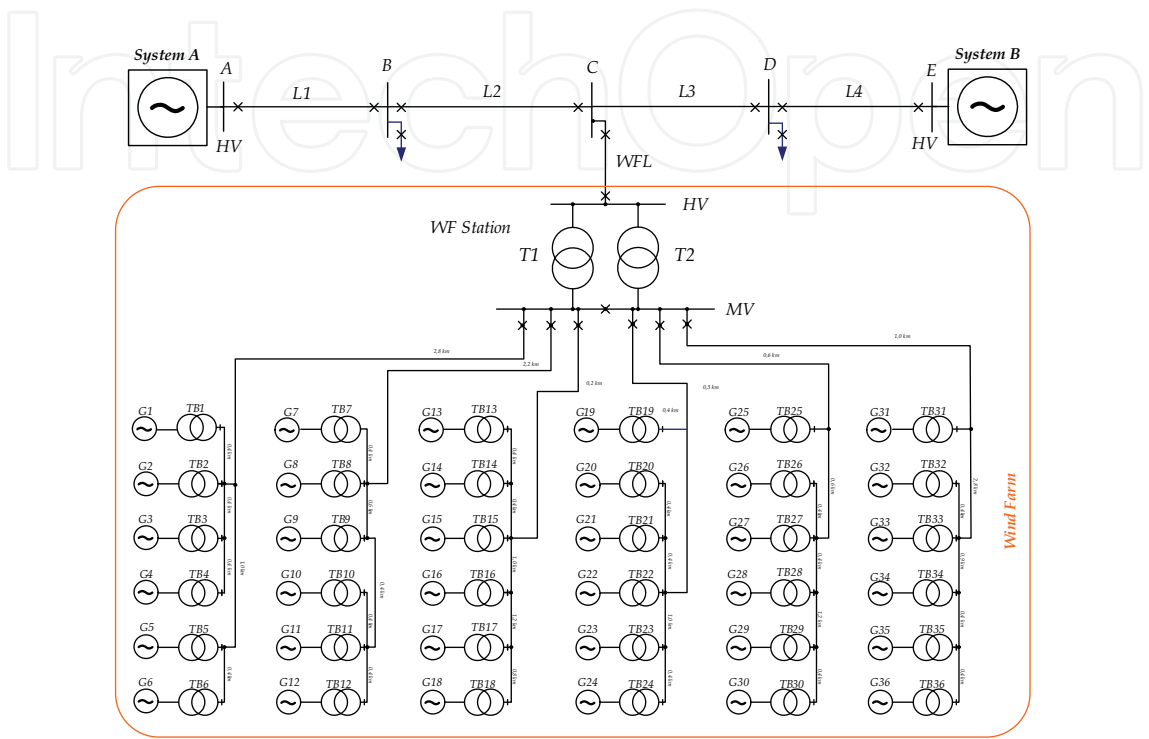


Fig. 1. Sample structure of internal electrical network of the 72 MW wind farm connected to the HV distribution network

There are different ways of connecting wind farms to the HV network depending, among other things, on the power level of a wind farm, distance to the HV substation and the number of wind farms connected to the sequencing lines. One can distinguish the following characteristic types of connections of wind farms to the transmission network:

- Connection in the three-terminal scheme (Fig. 2a). For this form of connection the lowest investment costs can be achieved. On the other hand, this form of connection causes several serious technical problems, especially for the power system automation. They are related to the proper faults detection and faults elimination in the surroundings of the wind farm connection point. Currently, this is not the preferred and recommended type of connection. Usually, the electrical power of such a wind farm does not exceed a dozen or so MW.
- Connection to the HV busbars of the existing substation in the series of lines (Fig. 2b). This is the most popular solution. The level of connected wind farms is typically in the range of 5 to 80 MW.
- Connection by the cut of the line (Fig. 3.). This entails building a new substation. If the farm is connected in the vicinity of an existing line, a separate wind farm feeder line is superfluous. Only cut ends of the line have to be guided to the new wind farm power substation. This substation can be made in the H configuration or the more complex 2

circuit-breaker (2CB) configuration (Fig. 3b). The topology of the substation depends on the number of the target wind farms connected to such a substation.

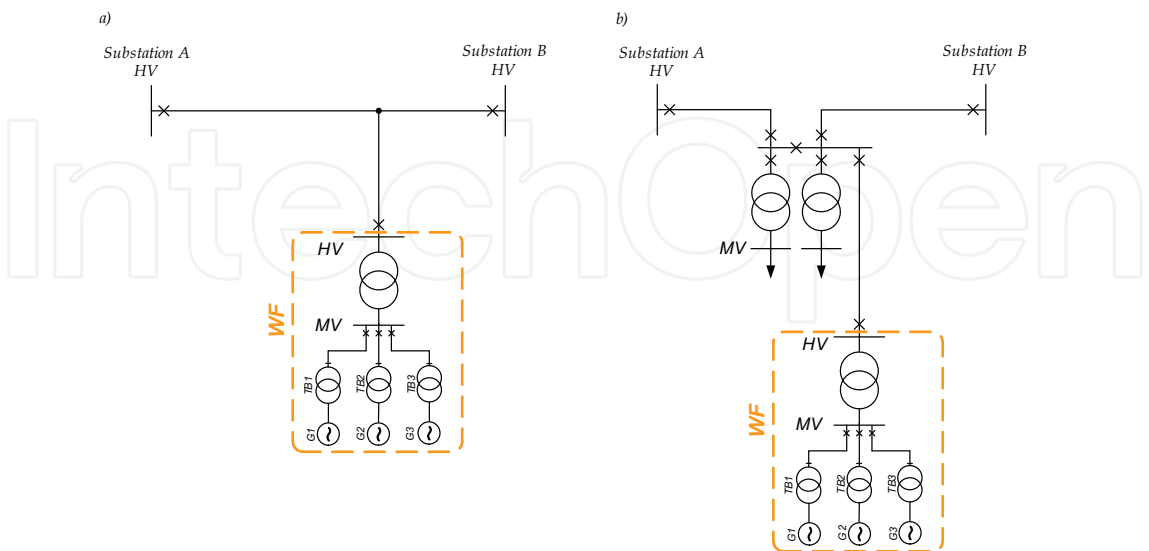


Fig. 2. Types of the wind farm connection to HV network: a) three terminal-line , b) connection to the busbars of existing HV/MV substation

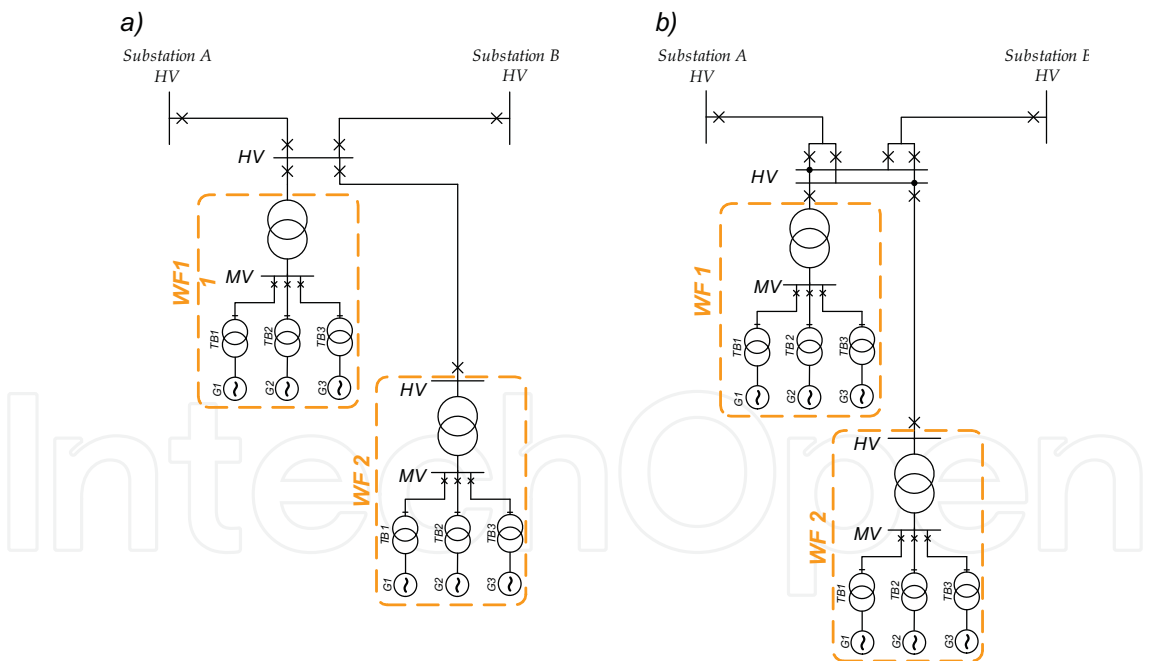


Fig. 3. Connection of the wind farm to the HV network by the cutting of line: a) substation in the H4 configuration, b) two-system 2CB configuration

- Connection to the HV switchgear of the EHV/HV substation bound to the transmission network. In this case one of the existing HV line bays (Fig. 4a) or the separate transformer (Fig. 4b) can be used. This form of connection is possible for wind farms of high level generating powers (exceeding 100 MW). The influence of such a connection on the proper functioning of the power protections is the lowest one.

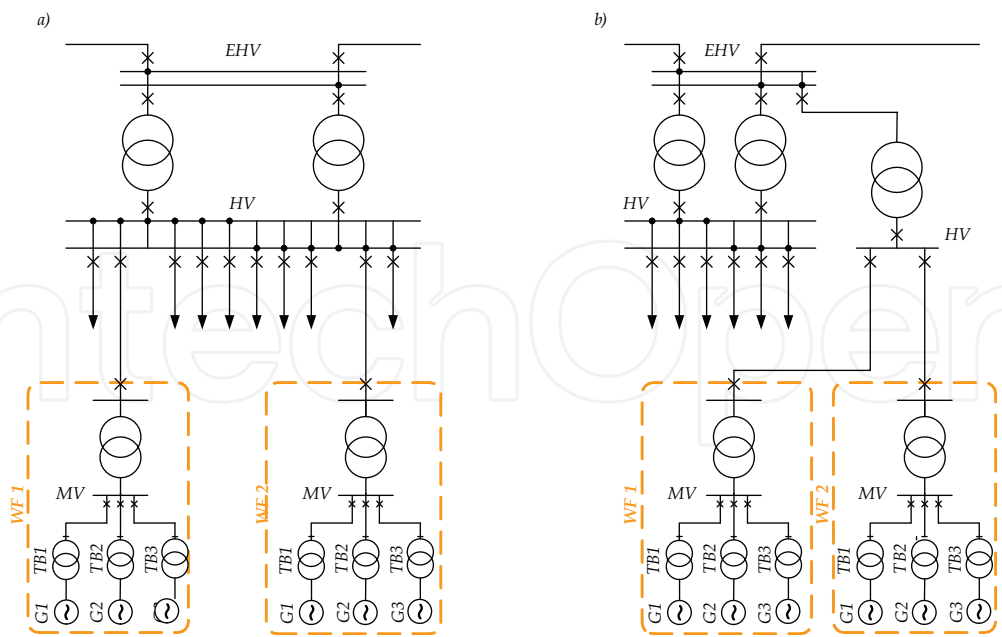


Fig. 4. Wind farm connection to the power system: a) by the existing switching bay of the EHV/HV substation, b) by the HV busbars of the separate EHV/HV transformer

- Connection of the wind farm by the high voltage AC/DC link (Fig. 5). This form is most commonly used for wind farms located on the sea and for different reasons cannot work synchronously with the electrical power system. Using a direct current link is useful for the control of operating conditions of the wind farm, however at the price of higher investments costs.

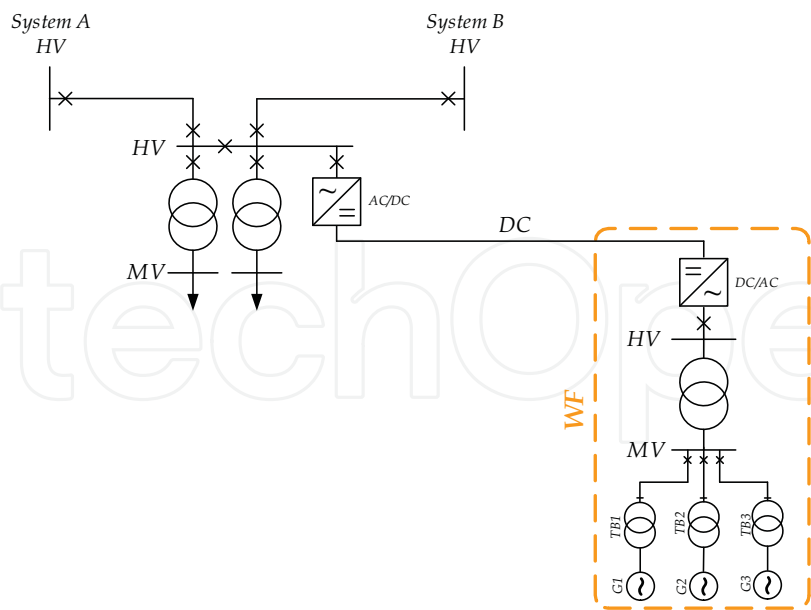


Fig. 5. Connection of the wind farm by the AC/DC link

Due to the limited number of system EHV/HV substations and the relatively high distances between substations and wind farms, most of them are connected to the existing or newly built HV/MV substations inside the HV line series.

3. Technical requirements for the dispersed power sources connected to the distribution network

Basic requirements for dispersed power sources are stipulated by a number of directives and instructions provided by the power system network operator. They contain a wide spectrum of technical conditions which must be met when such objects are connected to the distribution network. From the point of view of the power system automation, these requirements are mainly concerned with the possibilities of the power level and voltage regulation. Additionally, the behaviour of a wind farm during faults in the network and the functioning of power protection automation have to be determined. Wind farms connected to the HV distribution network should be equipped with the remote control, regulation and monitoring systems which enable following operation modes:

- operation without limitations (depending on the weather conditions),
- operation with an assumed *a priori* power factor and limited power generation,
- intervention operation during emergencies and faults in the power system (type of intervention is defined by the operator of the distribution network),
- voltage regulator at the connection point,
- participation in the frequency regulation (this type of work is suitable for wind farms of the generating power greater than 50 MW).

During faults in HV network, when significant changes (dips) of voltage occur, wind farm cannot loose the capability for reactive power regulation and should actively work towards sustaining the voltage level in the network. It also should maintain continuous operation in the case of faults in the distribution network which cause voltage dips at the wind farm connection point, of the times over the borderline shown in Fig. 6.

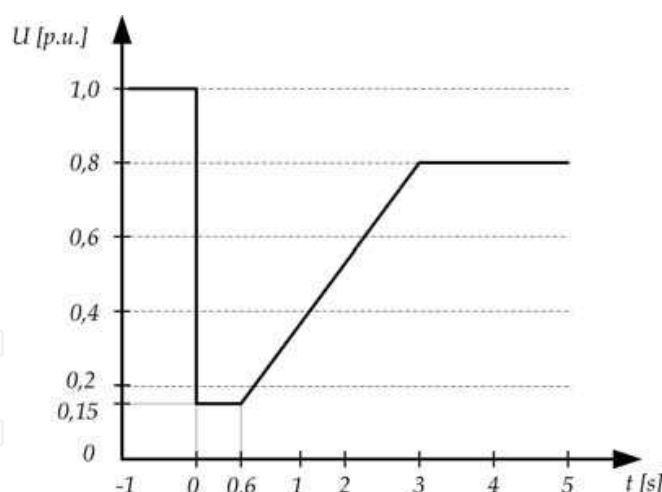


Fig. 6. Borderline of voltage level conditioning continuous wind farm operation during faults in the distribution network

4. Dispersed power generation sources in fault conditions

The behaviour of a power system in dynamic fault states is much more complicated for the reason of the presence of dispersed power sources than when only the conventional ones are in existence. This is a direct consequence of such factors as the technical construction of driving units, different types of generators, the method of connection to the distribution

network, regulators and control units, the presence of fault ride-through function as well as a wide range of the generating power determined by e.g. the weather conditions.

Taking the level of fault current as the division criteria, the following classification of dispersed power sources can be suggested:

- sources generating a constant fault current on a much higher level than the nominal current (mainly sources with synchronous generators),
- sources generating a constant fault current close to the nominal current (units with DFIG generators or units connected by the power converters with the fault ride-through function),
- sources not designed for operation in faulty conditions (sources with asynchronous generators or units with power converters without the fault ride-through function).

Sources with synchronous generators are capable of generating a constant fault current of higher level than the nominal one. This ability is connected with the excitation unit which is employed and with the voltage regulator. Synchronous generators with an electromechanical excitation unit are capable of holding up a three-phase fault current of the level of three times or higher than the nominal current for a few seconds. For the electronic (static) excitation units, in the case of a close three-phase fault, it is dropping to zero after the disappearance of transients. This is due to the little value of voltage on the output of the generator during a close three-phase fault.

For asynchronous generators, the course of a three-phase current on its outputs is only limited by the fault impedance. The fault current drops to zero in about $(0,2 \div 0,3)$ s. The maximum impulse current is close to the inrush current during the motor start-up of the generator (Lubošny, 2003). The value of such a current for typical machines is five times higher than the nominal current. This property makes it possible to limit the influence of such sources only on the initial value of the fault current and value of the impulse current.

The construction and parameters of the power converters in the power output circuit determine the level of fault current for such dispersed power sources. Depending on the construction, they generate a constant fault current on the level of its nominal current or are immediately cut off from the distribution network after a detection of a fault. If the latter is the case, only a current impulse is generated just after the beginning of a fault.

A common characteristic of dispersed sources cooperating with the power system is the fact that they can achieve local stability. Some of the construction features (power converters) and regulatory capabilities (reactive power, frequency regulation) make the dispersed power generation sources units highly capable of maintaining the stability in the local network area during the faulty conditions (Lubošny, 2003).

Dynamic states analyses must take into consideration the fact that present wind turbines are characterized by much higher resistance to faults (voltage dips) to be found in the power system than the conventional power sources based on the synchronous generators. A very important and useful feature of some wind turbines equipped with power converters, is the fact that they can operate in a higher frequency range $(43 \div 57 \text{ Hz})$ than in conventional sources $(47 \div 53 \text{ Hz})$ (Ungrad et al., 1995).

Dispersed generation may have a positive influence on the stability of the local network structures: *dispersed source – distribution network* during the faults. Whether or not it can be well exploited, depends on the proper functioning of the power system protection automation dedicated to the distribution network and dispersed power generation sources.

5. Influence of connecting dispersed power generating sources to the distribution network on the proper functioning of power system protections

In the Polish power system most of generating power plants (the so-called system power plants) are connected to the HV and EHV (220 kV and 400 kV) transmission networks. Next, HV networks are usually treated as distribution networks powered by the HV transmission networks. This results in the lack of adaptation of the power system protection automation in the distribution network to the presence of power generating sources on those (MV and HV) voltage levels.

Even more frequently, using of the DPGS, mainly wind farms, is the source of potential problems with the proper functioning of power protection automation. The basic functions vulnerable to the improper functioning in such conditions are:

- primary protection functions of lines,
- earth-fault protection functions of lines,
- restitution automation, especially auto-reclosing function,
- overload functions of lines due the application of high temperature low sag conductors and the thermal line rating,
- functions controlling an undesirable transition to the power island with the local power generation sources.

The subsequent part of this paper will focus only on the influence of the presence of the wind farms on the correctness of action of impedance criteria in distance protections.

5.1 Selected aspects of an incorrect action of the distance protections in HV lines

Distance protection provides short-circuit protection of universal application. It constitutes a basis for network protection in transmission systems and meshed distribution systems. Its mode of operation is based upon the measurement and evaluation of the short-circuit impedance, which in the typical case is proportional to the distance to the fault. They rarely use pilot lines in the 110 kV distribution network for exchange of data between the endings of lines. For the primary protection function, comparative criteria are also used. They take advantage of currents and/or phases comparisons and use of pilot communication lines. However, they are usually used in the short-length lines (Ungrad et al., 1995).

The presence of the DPGS (wind farms) in the HV distribution network will affect the impedance criteria especially due to the factors listed below:

- highly changeable value of the fault current from a wind farm. For wind farms equipped with power converters, taking its reaction time for a fault, the fault current is limited by them to the value close to the nominal current after typically not more than 50 ms. So the impact of that component on the total fault current evaluated in the location of protection is relatively low.
- intermediate in-feed effect at the wind farm connection point. For protection realizing distance principles on a series of lines, this causes an incorrect fault localization both in the primary and the back-up zones,
- high dynamic changes of the wind farm generating power. Those influence the more frequent and significant fluctuations of the power flow in the distribution network. They are not only limited to the value of the load currents but also to changes of their directions. In many cases a load of high values must be transmitted. Thus, it is necessary to use wires of higher diameter or to apply high temperature low sag

conductors or thermal line rating schemes (dynamically adjusting the maximum load to the seasons or the existing weather conditions). Operating and load area characteristics may overlap in these cases.

Setting distance protections for power lines

In the case of distance protections, a three-grading plan (Fig. 7) is frequently used. Additionally, there are also start-up characteristic and the optional reverse zone which reach the busbars.

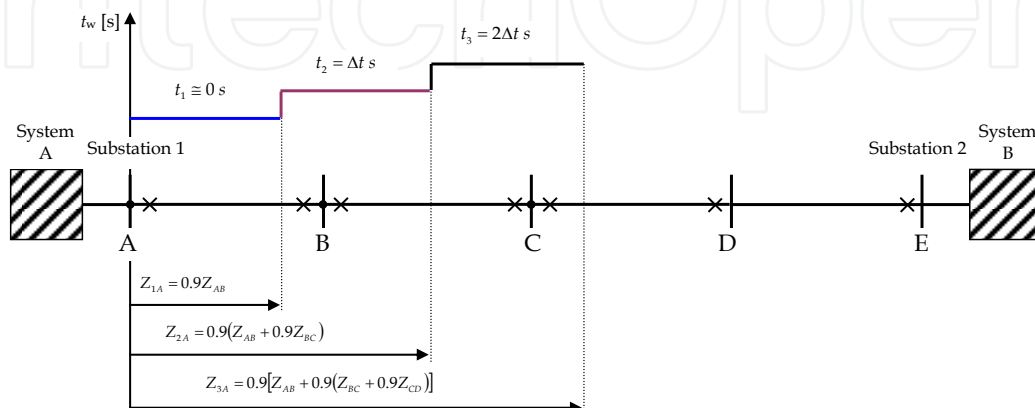


Fig. 7. Three-grading plan of distance protection on series of lines

The following principles can be used when the digital protection terminal is located in the substation A (Fig. 7) (Ziegler, 1999):

- impedance reach of the first zone is set to 90 % of the A-B line-length

$$Z_{1A} = |0.9 \underline{Z}_{AB}| \quad (1)$$

tripping time $t_1=0$ s;

- impedance reach of the second zone cannot exceed the impedance reach of the first zone of protection located in the substation B

$$Z_{2A} = |0.9(\underline{Z}_{AB} + 0.9 \underline{Z}_{BC})| \quad (2)$$

tripping time should be one step higher than the first one $t_2=\Delta t$ s from the range of (0.3÷0.5) s. Typically for the digital protections and fast switches, a delay of 0.3 s is taken;

- impedance reach of the third zone is maximum 90% of the second zone of the shortest line outgoing from the subsubstation B:

$$Z_{3A} = |0.9[\underline{Z}_{AB} + 0.9(\underline{Z}_{BC} + 0.9 \underline{Z}_{CD})]| \quad (3)$$

For the selectivity condition, tripping time for this zone cannot be shorter than $t_3=2\Delta t$ s.

Improper fault elimination due to the low fault current value

As mentioned before, when the fault current flowing from the DPGS is close to the nominal current, in most of cases overcurrent and distance criteria are difficult or even impossible to apply for the proper fault elimination (Pradhan & Geza, 2007). Figure 8 presents sample

courses of the rms value of voltage U , current I , active and reactive power (P and Q) when there are voltage dips caused by faults in the network. The recordings are from a wind turbine equipped with a 2 MW generator with a fault ride-through function (Datasheet, Vestas). This function permits wind farm operation during voltage dips, which is generally required for wind farms connected to the HV networks.

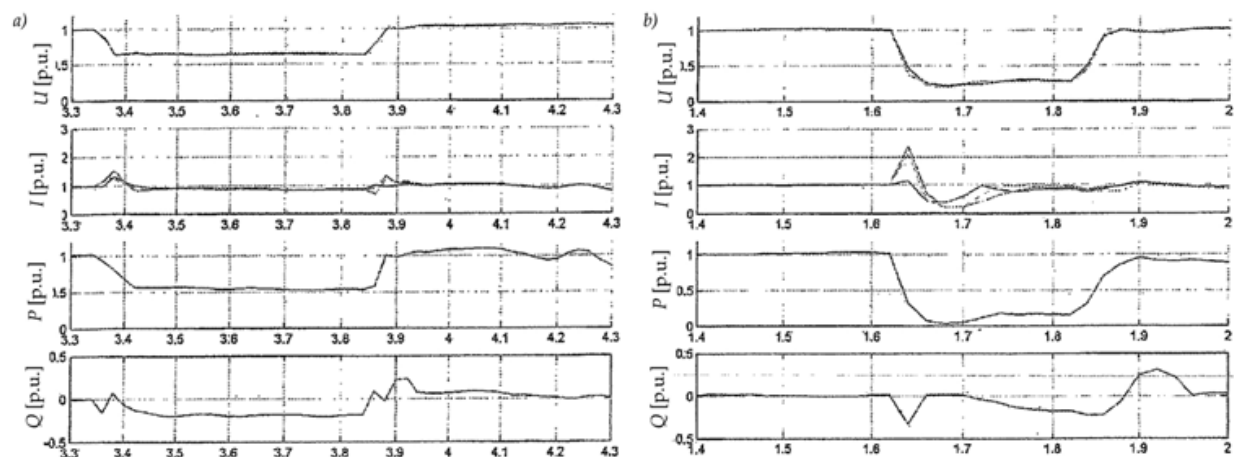


Fig. 8. Courses of electric quantities for Vestas V80 wind turbine of 2 MW: a) voltage dip to $0.6 U_N$, b) voltage dip to $0.15 U_N$ (Datasheet, Vestas)

Analyzing the course of the current presented in Fig. 8, it can be observed that it is close to the nominal value and in fact independent a of voltage dip. Basing on the technical data it is possible to approximate t_1 time, when the steady-state current will be close to the nominal value (Fig. 9).

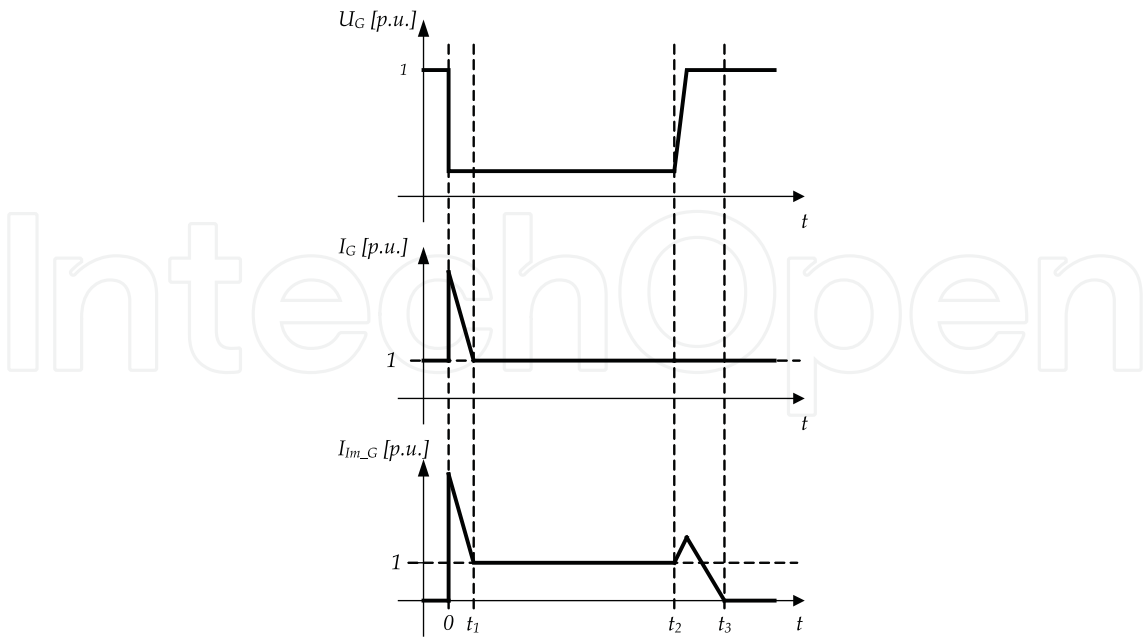


Fig. 9. Linear approximation of current and voltage values for the wind turbine with DFIG generator during voltage dips: U_G – voltage on generator outputs, I_G – current on generator outputs, I_{lm_G} – generator reactive current, $t_1 \approx 50$ ms, $t_3 - t_2 \approx 100$ ms

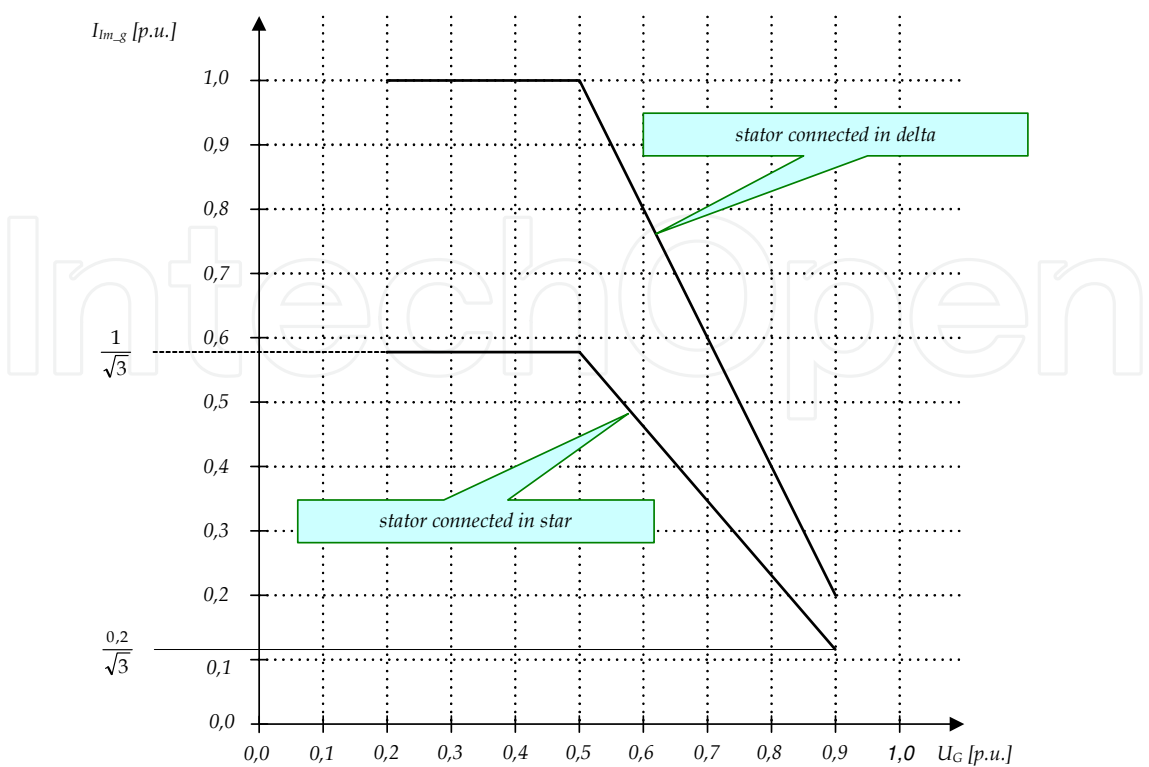


Fig. 10. Course of the wind turbine reactive current

The negative influence of the low value steady current from the wind farm is cumulating especially when the distribution network is operating in the open configuration (Fig. 11).

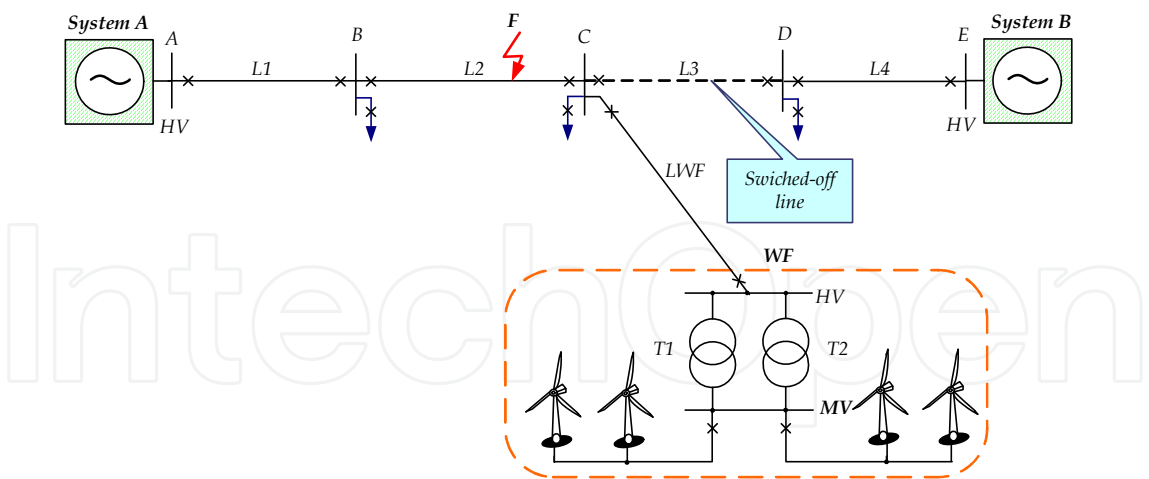


Fig. 11. Wind farm in the distribution network operating in the open configuration

The selected wind turbine is the one most frequently used in the Polish power grid. The impulse current at the beginning of the fault is reduced to the value of the nominal current after 50 ms. Additionally, the current has the capacitance character and is only dependent on the stator star/delta connection. This current has the nominal value for delta connection (high rotation speed of turbine) and nominal value divided by $\sqrt{3}$ for the star connection as presented in Fig. 9.

Reaction of protection automation systems in this configuration can be estimated comparing the fault current to the pick-up currents of protections. For a three-phase fault at point F (Fig. 11) the steady fault current flowing through the wind farm cannot exceed the nominal current of the line. The steady fault current of the single wind turbine of $P_N=2$ MW ($S_N=2.04$ MW) is $I_k = I_{NG} = 10.7$ A at the HV side (delta stator connection). However initial fault current I_k'' is 3,3 times higher than the nominal current ($I_k'' = 35.31$ A). It must be emphasized that the number of working wind turbines at the moment of a fault is not predictable. This of course depends on weather conditions or the network operator's requirements. All these influence a variable fault current flowing from a wind farm. In many cases there is a starting function of the distance protection in the form of a start-up current at the level of 20% of the nominal current of the protected line. Taking 600 A as the typical line nominal current, even several wind turbines working simultaneously are not able to exceed the pick-up value both in the initial and the steady state fault conditions. When the impedance function is used for the pick-up of the distance protection, the occurrence of high inaccuracy and fluctuations of measuring impedance parameters are expected, especially in the transient states from the initial to steady fault conditions.

The following considerations will present a potential vulnerability of the power system distribution networks to the improper (missing) operation of power line protections with connected wind farms. In such situations, when there is a low fault current flow from a wind farm, even using the alternative comparison criteria will not result in the improvement of its operation. It is because of the pick-up value which is generally set at $(1,2 \div 1,5) I_N$.

To minimize the negative consequences of functioning of power system protection automation in HV network operating in an open configuration with connected wind farms, the following instructions should be taken:

- limiting the generated power and/or turning off the wind farm in the case of a radial connection of the wind farm with the power system. In this case, as a result of planned or fault switch-offs, low fault WF current occurs,
- applying distance protection terminals equipped with the weak end infeed logic on all of the series of HV lines, on which the wind farm is connected. The consequences are building up the fast teletransmission network and relatively high investment costs,
- using banks of settings, configuring adaptive distance protection for variant operation of the network structure causing different fault current flows. When the HV distribution network is operating in a close configuration, the fault currents considerably exceed the nominal currents of power network elements. In the radial configuration, the fault current which flows from the local power source will be under the nominal value.

Selected factors influencing improper fault location of the distance protections of lines

In the case of modifying the network structure by inserting additional power sources, i.e. wind farms, the intermediate in-feeds occur. This effect is the source of impedance paths measurement errors, especially when a wind farm is connected in a three-terminal configuration. Figure 12a shows the network structure and Fig. 12b a short-circuit equivalent scheme for three-phase faults on the M-F segment. Without considering the measuring transformers, voltage \underline{U}_p in the station A is:

$$\underline{U}_p = \underline{Z}_{AM} \underline{I}_A + \underline{Z}_{MF} \underline{I}_Z = \underline{Z}_{AM} \underline{I}_A + \underline{Z}_{MF} (\underline{I}_A + \underline{I}_{WF}) \quad (4)$$

On the other hand current I_p measured by the protection in the initial time of fault is the fault current I_A flowing in the segment A-M. Thus the evaluated impedance is:

$$\underline{Z}_p = \frac{\underline{U}_p}{\underline{I}_p} = \frac{\underline{Z}_{AM}\underline{I}_A + \underline{Z}_{MF}(\underline{I}_A + \underline{I}_{WF})}{\underline{I}_A} = \underline{Z}_{AM} + \underline{Z}_{MF}\left(1 + \frac{\underline{I}_{WF}}{\underline{I}_A}\right) = \underline{Z}_{AM} + \underline{Z}_{MF}k_{if} \tag{5}$$

where:
 \underline{U}_p – positive sequence voltage component on the primary side of voltage transformers at point A,
 \underline{I}_p – positive sequence current component on the primary side of current transformers at point A,
 \underline{I}_A – fault current flowing from system A,
 \underline{I}_{WF} – fault current flowing from WF,
 \underline{Z}_{AM} – impedance of the AM segment,
 \underline{Z}_{MF} – impedance of the MF segment,
 k_{if} – intermediate in-feed factor.

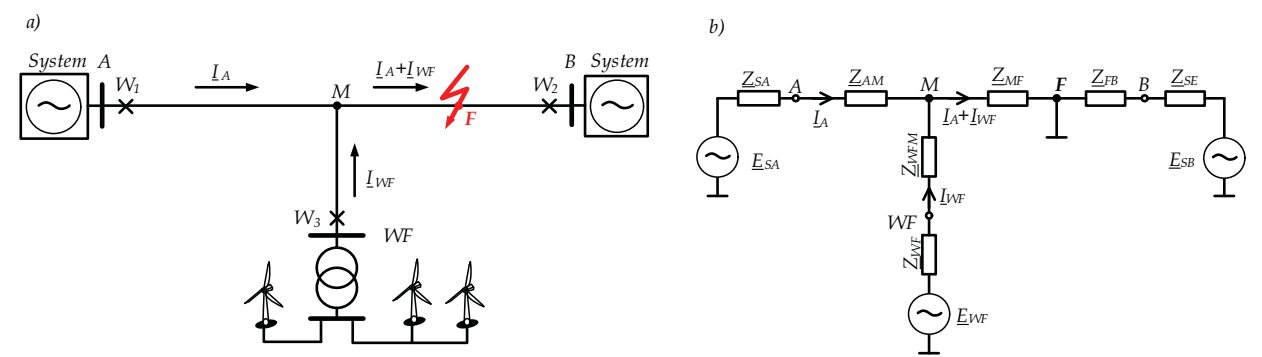


Fig. 12. Teed feeders configuration a) general scheme, b) equivalent short-circuit scheme.
It is evident that estimated from (5) impedance is influenced by error ΔZ :

$$\underline{\Delta Z} = \underline{Z}_{MF} \frac{\underline{I}_{WF}}{\underline{I}_A} \tag{6}$$

The error level is dependent on the quotient of fault current I_Z from system A and power source WF (wind farm). Next the error is always positive so the impedance reaches of the operating characteristics are shorter. Evaluating the error level from the impedance of the equivalent short-circuit:

$$\underline{\Delta Z} = \underline{Z}_{MF} \frac{\underline{Z}_{SA} + \underline{Z}_{AM}}{\underline{Z}_{WF} + \underline{Z}_{WFM}} \tag{7}$$

Equation (7) shows the significant impact on the error level of short-circuit powers (impedances of power sources), location of faults ($\underline{Z}_{AM}, \underline{Z}_{FWM}$) and types of faults. Minimizing possible errors in the evaluation of impedance can be achieved by modifying the reaches of operating characteristics covering the WF location point. Thus the reaches of the second and the third zone of protection located at point A (Fig. 7) are:

$$Z_{2A} = \left| 0.9 \left(\underline{Z}_{AB} + 0.9 \underline{Z}_{BC} \underline{k}_{if} \right) \right| = \left| 0.9 \left[\underline{Z}_{AB} + 0.9 \underline{Z}_{BC} \left(1 + \frac{\underline{I}_{WF}}{\underline{I}_A} \right) \right] \right| \quad (8)$$

$$Z_{3A} = \left| 0.9 \left[\underline{Z}_{AB} + 0.9 \left(\underline{Z}_{BC} + 0.9 \underline{Z}_{CD} \right) \underline{k}_{if} \right] \right| = \left| 0.9 \left[\underline{Z}_{AB} + 0.9 \left(\underline{Z}_{BC} + 0.9 \underline{Z}_{CD} \right) \left(1 + \frac{\underline{I}_{WF}}{\underline{I}_A} \right) \right] \right| \quad (9)$$

It is also necessary to modify of the first zone, i.e.:

$$Z_{1A} = \left| 0.9 \underline{Z}_{AB} \underline{k}_{if} \right| = \left| 0.9 \underline{Z}_{AB} \left(1 + \frac{\underline{I}_{WF}}{\underline{I}_A} \right) \right| \quad (10)$$

This error correction is successful if the error level described by equations (6) and (7) is constant. But for wind farms this is a functional relation. The arguments of the function are, among others, the impedance of WF \underline{Z}_{WF} and a fault current \underline{I}_{WF} . These parameters are dependent on the number of operating wind turbines, distance from the ends of the line to the WF connection point (point M in Fig. 12a), fault location and the time elapsed from the beginning of a fault (including initial or steady fault current of WF).

As mentioned before, the three-terminal line connection of the WF in faulty conditions causes shortening of reaches of all operating impedance characteristics in the direction to the line. This concerns both protections located in substation A and WF. For the reason of reaching reduction level, it can lead to:

- extended time of fault elimination, e.g. fault elimination will be done with the time of the second zone instead of the first one,
- improper fault elimination during the auto-reclosure cycles. This can occurs when during the intermediate in-feed the reaches of the first extended zones overcome shortening and will not reach full length of the line. Then what cannot be reached is simultaneously cutting-off the fault current and the pick-up of auto-reclosure automation on all the line ends.

In Polish HV distribution networks the back-up protection is usually realized by the second and third zones of distance protections located on the adjacent lines. With the presence of the WF (Fig. 13), this back-up protection can be ineffective.

As an example, in connecting WF to substation C operating in a series of lines A-E what should be expected is the miscalculation of impedances in the case of intermediate in-feed in substation C from the direction of WF. The protection of line L2 located in substation B, when the fault occurs at point F on the line L3, "sees" the impedance vector in its second or third zone. The error can be obtained from the equation:

$$\underline{Z}_{pB} = \frac{\underline{U}_{pB}}{\underline{I}_{pB}} = \frac{\underline{I}_{L2} \underline{Z}_{BC} + (\underline{I}_{L2} + \underline{I}_{WF}) \underline{Z}_{CF}}{\underline{I}_{L2}} = \underline{Z}_{BC} + \underline{Z}_{CF} + \Delta \underline{Z}_{pB} \quad (11)$$

where:

\underline{U}_{pB} – positive sequence voltage on the primary side of voltage transformers at point B,

\underline{I}_{pB} – positive sequence current on the primary side of current transformers at point B,

\underline{I}_{L2} – fault current flowing by the line L2 from system A,

\underline{I}_{WF} – fault current from WF,

\underline{Z}_{BC} – line L2 impedance,
 \underline{Z}_{CF} – impedance of segment CF of the line L3
and the error ΔZ_{pB} is defined as:

$$\Delta Z_{pB} = \underline{Z}_{CF} \left(\frac{I_{WF}}{I_{L2}} \right).$$

(12)

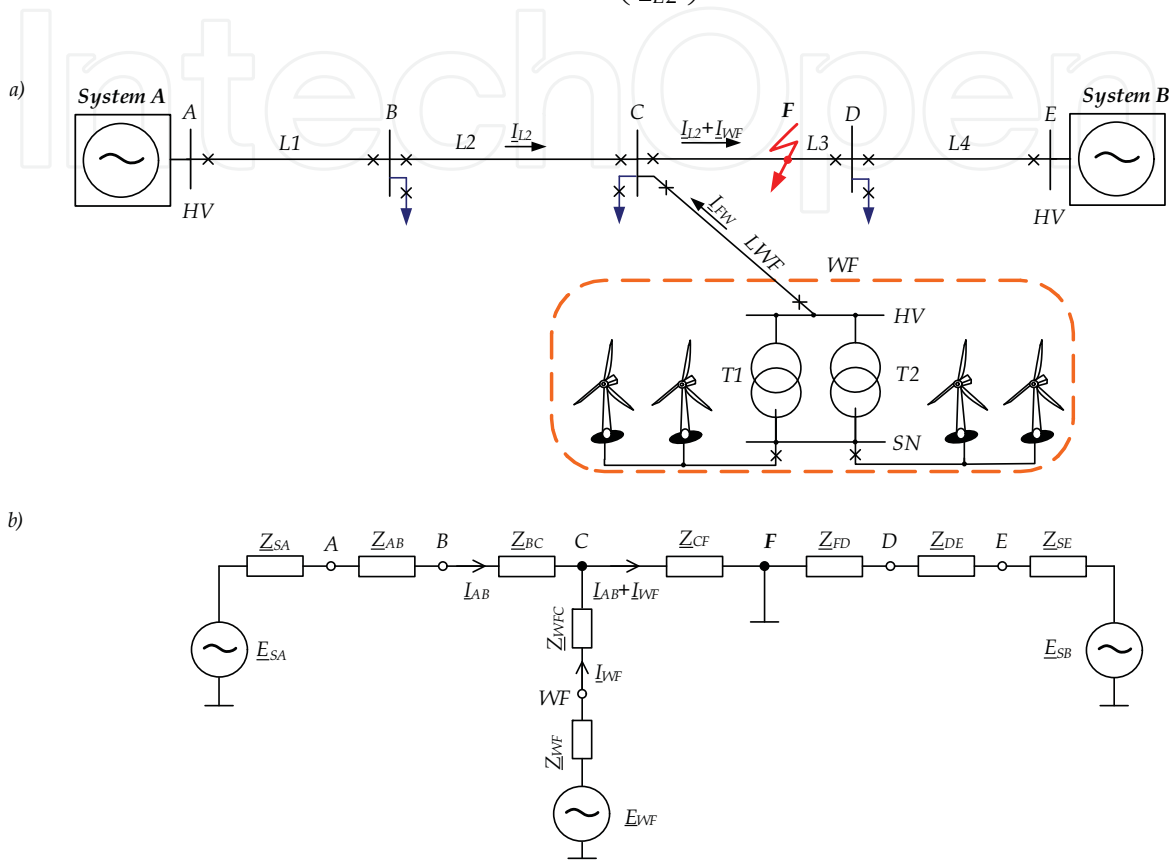


Fig. 13. Currents flow after the WF connection to substation C: a) general scheme, b) simplified equivalent short-circuit scheme

It must be emphasized that, as before, also the impedance reaches of second and third zones of LWF protection located in substation WF are reduced due to the intermediate in-feed. Due to the importance of the back-up protection, it is essential to do the verification of the proper functioning (including the selectivity) of the second and third zones of adjacent lines with wind farm connected. However, due to the functional dynamic relations, which cause the miscalculations of the impedance components, preserving the proper functioning of the distance criteria is hard and requires strong teleinformatic structure and adaptive decision-making systems (Halinka et al., 2006).

Overlapping of the operating and admitted load characteristics

The number of connected wind farms has triggered an increase of power transferred by the HV lines. As far as the functioning of distance protection is concerned, this leads to the increase of the admitted load of HV lines and brings closer the operating and admitted load characteristics. In the case of non-modified settings of distance protections this can lead to the overlapping of these characteristics (Fig 14).

The situation when such characteristics have any common points is unacceptable. This results in unneeded cuts-off during the normal operation of distribution network. Unneeded cuts-off of highly loaded lines lead to increases of loads of adjacent lines and cascading failures potentially culminating in blackouts.

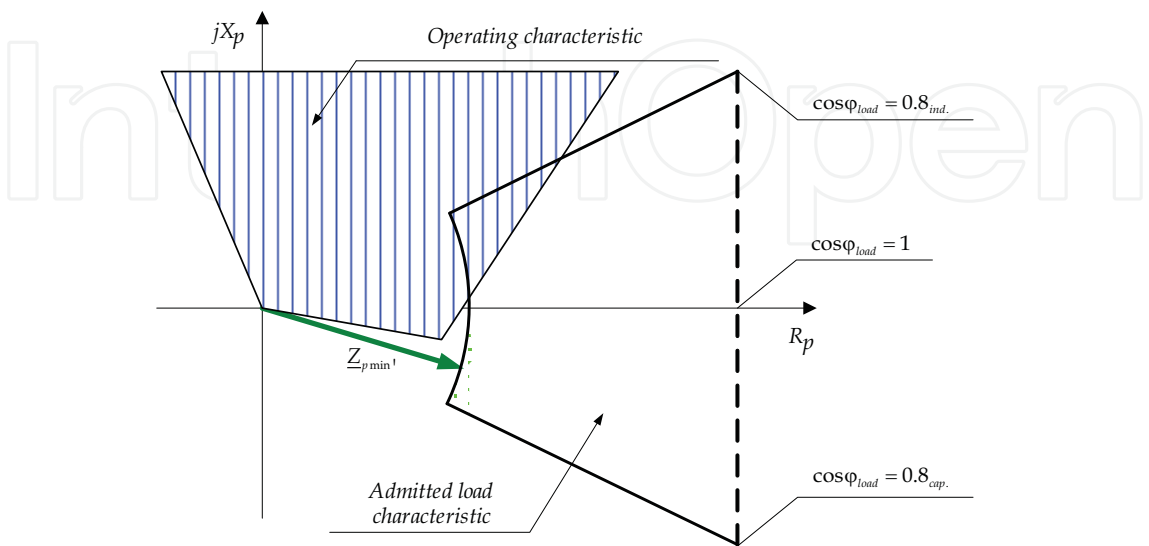


Fig. 14. Overlapping of operating and admitted load characteristics

The impedance area covering the admitted loads of a power line is dependent on the level and the character of load. This means that the variable parameters are both the amplitude and the phase part of the impedance vector. In normal operating conditions the amplitude of load impedance changes from Z_{pmin} practically to the infinity (unloaded line). The phase of load usually changes from $\cos\varphi = 0.8_{ind}$ to $\cos\varphi = 0.8_{cap}$. The expected Z_{pmin} can be determined by the following equation (Ungrad et al., 1995), (Schau et al., 2008):

$$Z_{pmin} = \frac{U_{pmin}^2}{S_{pmax}} = \frac{U_{pmin}}{\sqrt{3} \cdot I_{pmax}} , \tag{13}$$

where:

- U_{pmin} – minimal admitted operating voltage in kV (usually $U_{pmin} = 0,9 U_N$),
- S_{pmax} – maximum apparent power in MVA,
- I_{pmax} – maximum admitted load.

A necessary condition of connecting DPGS to the HV network is researching whether the increase of load (especially in faulty conditions e.g. one of the lines is falling out) is not leading to an overlap. Because of the security reasons and the falsifying factors influencing the impedance evaluation, it is assumed that the protection will not unnecessarily pick-up if the impedance reach of operating zones will be shorter than 80% of the minimal expected load. This requirement will be practically impossible to meet especially when the MHO starting characteristics are used (Fig 15a). There are more possibilities when the protection realizes a distance protection function with polygonal characteristics (Fig. 15b).

Using digital distance protections with polygonal characteristics is also very effective for HV lines equipped with high temperature low sag conductors or thermal line rating. In this case

the load can increase 2.5 times. Figure 16 shows the adaptation of an impedance area to the maximum expected power line load. Of course this implies serious problems with the recognition of faults with high resistances.

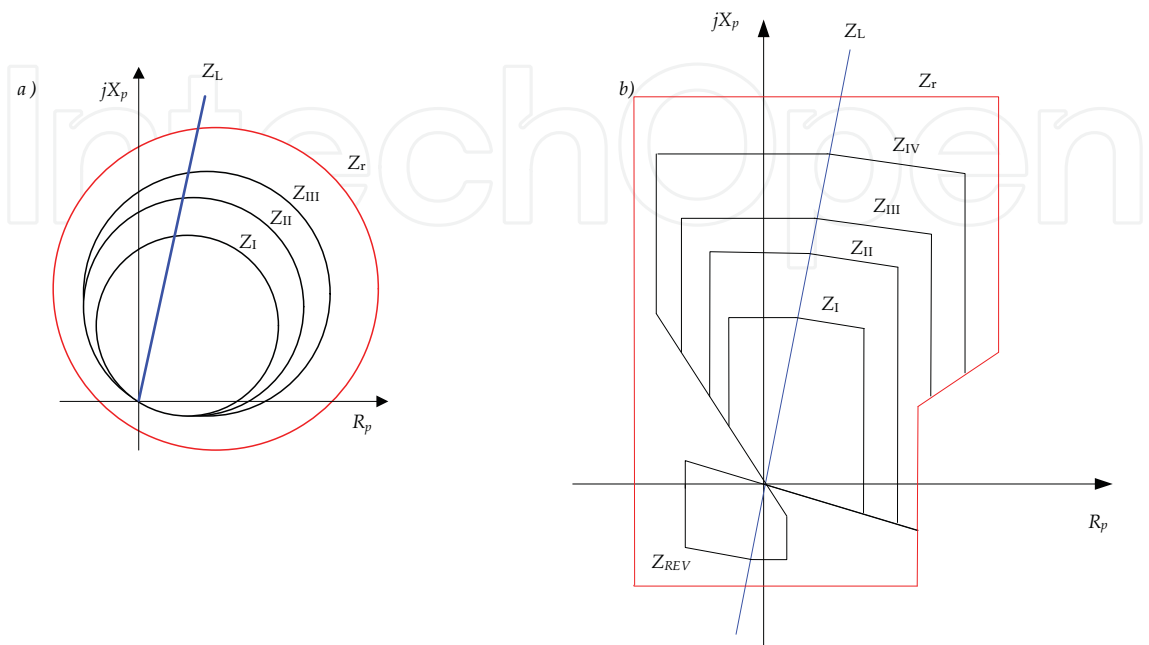


Fig. 15. Starting and operating characteristics a) MHO, b) polygonal

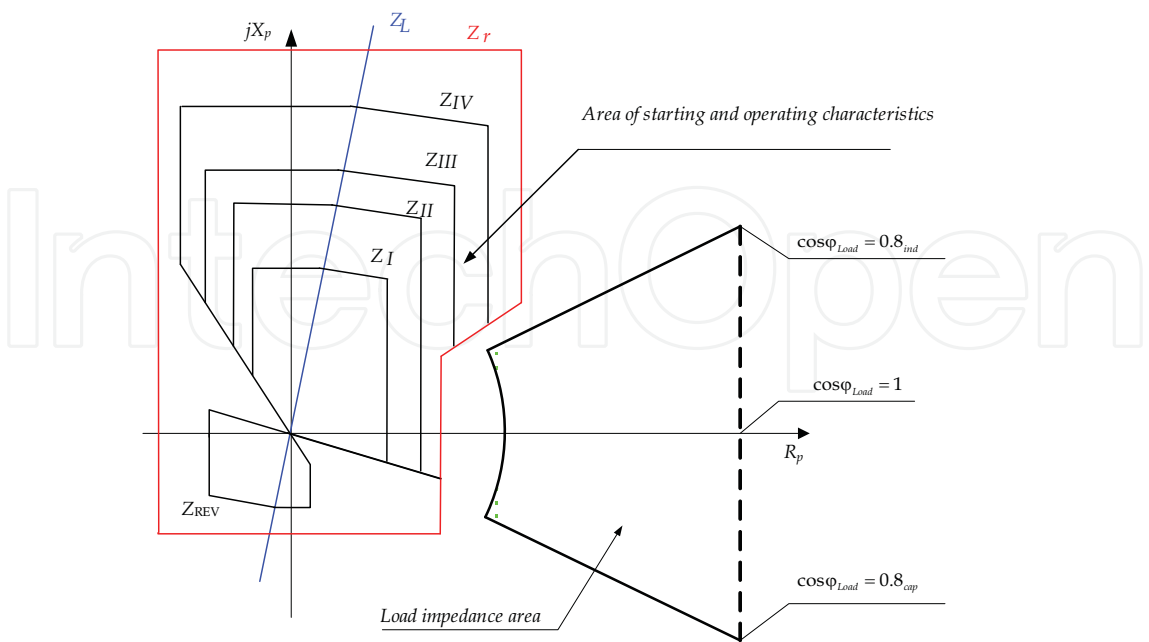


Fig. 16. Adaptation of operating characteristics to the load impedance area

5.2 Simulations

Figure 17 shows the network structure taken for the determination of the influence of selected factors on the impedance evaluation error. This is a part of the 110 kV network of the following parameters:

- short-circuit powers of equivalent systems: $S''_{kA} = 1000 \text{ MVA}$, $S''_{kB} = 500 \text{ MVA}$;
- wind farm consists of 30 wind turbines using double fed induction generators of the individual power $P_{jN}=2 \text{ MW}$ with a fault ride-through function. Power of a wind farm is changing from 10% to 100% of the nominal power of the wind farm. WF is connected in the three-terminal line scheme,
- overhead power line AB:
- length: 30 km; resistance per km: $r_1=0.12 \text{ }\Omega/\text{km}$, reactance per km $x_j=0.4 \text{ }\Omega/\text{km}$
- overhead power output line from WF:
- length: 2 km; resistance per km: $r_1=0.12 \text{ }\Omega/\text{km}$, reactance per km $x_j=0.4 \text{ }\Omega/\text{km}$
- metallic three-phase fault on line AB between the M connection point and 100% of the line L_{A-B} length.

Initial and steady fault currents from the wind farm and system A have been evaluated for these parameters. It has been assumed that phases of these currents are equal. The initial fault current of individual wind turbines will be limited to 330% of the nominal current of the generator and wind turbines will generate steady fault current on the level of 110% of the nominal current of the generator. The following examples will now be considered.

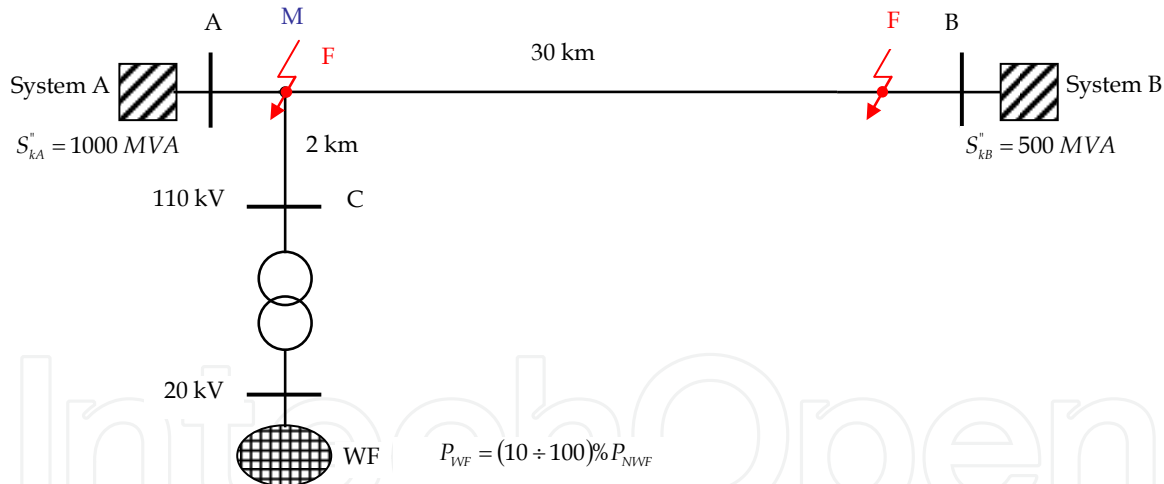


Fig. 17. Network scheme for simulations

Example 1

The network is operating in quasi-steady conditions. The farm is generating power of 60 MW and is connected at 10 % of the L_{A-B} line length. The location of a fault changeable from 20 % to 100 % of the L_{A-B} length with steps of 10 %. Table 1 presents selected results of simulations for faults of times not exceeding 50 ms. Results take into consideration the limitation of fault currents on the level of 330% of the nominal current of the generator. By analogy, Table 2 shows the results when the limitation is 110 % after a reaction of the control units.

Fault location		I_A	I_C	I_C/I_A	ΔR	ΔX	$\delta_{R\%}$	$\delta_{X\%}$	R_{LAF}	X_{LAF}
l	$x\% \underline{Z}_{LAB}$									
[km]	[%]	[kA]	[kA]	[-]	[Ω]	[Ω]	[%]	[%]	[Ω]	[Ω]
6	20	3.93	0.801	0.204	0.073	0.245	10.191	10.191	0.720	2.400
9	30	3.591	0.732	0.204	0.147	0.489	13.590	13.590	1.080	3.600
12	40	3.305	0.674	0.204	0.220	0.734	15.295	15.295	1.440	4.800
15	50	3.061	0.624	0.204	0.294	0.979	16.308	16.308	1.800	6.000
18	60	2.851	0.581	0.204	0.367	1.223	16.982	16.982	2.160	7.200
21	70	2.667	0.545	0.204	0.441	1.471	17.516	17.516	2.520	8.400
24	80	2.505	0.511	0.204	0.514	1.714	17.849	17.849	2.880	9.600
27	90	2.362	0.481	0.204	0.586	1.955	18.101	18.101	3.240	10.800
30	100	2.234	0.455	0.204	0.660	2.200	18.330	18.330	3.600	12.000

Table 1. Initial fault currents and impedance errors for protection located in station A depending on the distance to the location of a fault (Case 1)

where:

l – distance to a fault from station A,

$x\% \underline{Z}_{LAB}$ – distance to a fault in the percentage of the L_{AB} length,

I_A – rms value of the initial fault current flowing from system A to the point of fault,

I_C – rms value of the initial current flowing from WF to the point of a fault,

ΔR – absolute error of the resistance evaluation of the impedance algorithm,

$\Delta R = \text{Re}\{(I_C/I_A) \underline{Z}_{LMF}\}$,

ΔX – absolute error of the reactance evaluation of the impedance algorithm,

$\Delta X = \text{Im}\{(I_C/I_A) \underline{Z}_{LMF}\}$,

R_{LAF} – real value of the resistance of the fault loop,

X_{LAF} – real value of the reactance of the fault loop,

$\delta_{R\%}$ – relative error of the evaluation of the resistance $\delta_{R\%} = \Delta R/R_{LAF}$,

$\delta_{X\%}$ – relative error of the evaluation of the resistance, $\delta_{X\%} = \Delta X/X_{LAF}$.

Fault location		$I_{A(u)}$	$I_{C(u)}$	$I_{C(u)}/I_{A(u)}$	ΔR	ΔX	$\delta_{R\%}$	$\delta_{X\%}$
l	$x\% \underline{Z}_{LAB}$							
[km]	[%]	[kA]	[kA]	[-]	[Ω]	[Ω]	[%]	[%]
6	20	3.986	0.328	0.082	0.030	0.099	4.114	4.114
9	30	3.685	0.328	0.089	0.064	0.214	5.934	5.934
12	40	3.425	0.328	0.096	0.103	0.345	7.182	7.182
15	50	3.199	0.328	0.103	0.148	0.492	8.203	8.203
18	60	3	0.328	0.109	0.197	0.656	9.111	9.111
21	70	2.824	0.328	0.116	0.251	0.836	9.955	9.955
24	80	2.666	0.328	0.123	0.310	1.033	10.765	10.765
27	90	2.525	0.328	0.130	0.374	1.247	11.547	11.547
30	100	2.398	0.328	0.137	0.443	1.477	12.310	12.310

Table 2. Steady fault currents and impedance errors for protection located in station A depending on the distance to the location of a fault (Case 2)

where:

$I_{A(u)}$ - rms value of steady fault current flowing from system A to the point of a fault,

$I_{C(u)}$ - rms value of steady fault current flowing from WF to the point of a fault,

The above-mentioned tests confirm that the presence of sources of constant generated power (WF) brings about the miscalculation of impedance components. The error is rising with the distancing from busbars in substation A to the point of a fault, but does not exceed 20 %. It can be observed at the beginning of a fault that the error level is higher than in the case of action of the wind farm control units. It is directly connected with the quotient of currents from system A and WF. In the first case it is constant and equals 0.204. In the second one it is lower but variable and it is rising with the distance from busbars of substation A to the point of a fault.

From the point of view of distance protection located in station C powered by WF, the error level of evaluated impedance parameters is much higher and exceeds 450 %. It is due to the high I_A/I_C ratio which is 4.9. Figure 18 shows a comparison of a relative error of estimated reactance component of the impedance fault loop for protection located in substation A (system A) and station C (WF).

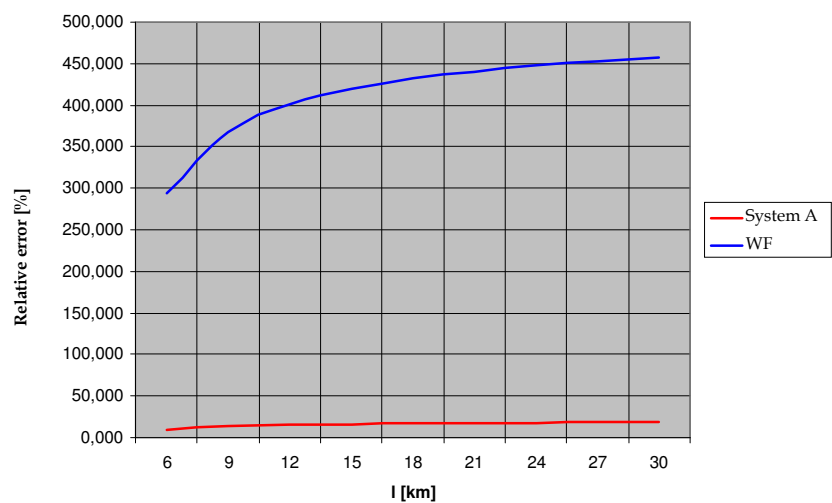


Fig. 18. Relative error (%) of reactance estimation in distance protection in substation A and C in relation to the distance to a fault

Attempting to compare estimates of impedance components for distance protections in substations A, B and C in relation to the distance to a fault, the following analysis has been undertaken for the network structure as in Fig. 19. Again a three-terminal line of WF connection has been chosen as the most problematic one for power system protections. For this variant WF consists of 25 wind turbines equipped as before with DFIG generators each of 2 MW power. The selection of such a type of generator is dictated by its high fault currents when compared with generators with power converters in the power output path and the popularity of the first ones.

Figure 20 shows the influence of the location of a fault on the divergence of impedance components evaluation in substations A, B and C in comparison to the real expected values. The presented values are for the initial time of a three-phase fault on line A-B with the assumption that all wind turbines are operating simultaneously, generating the nominal power.

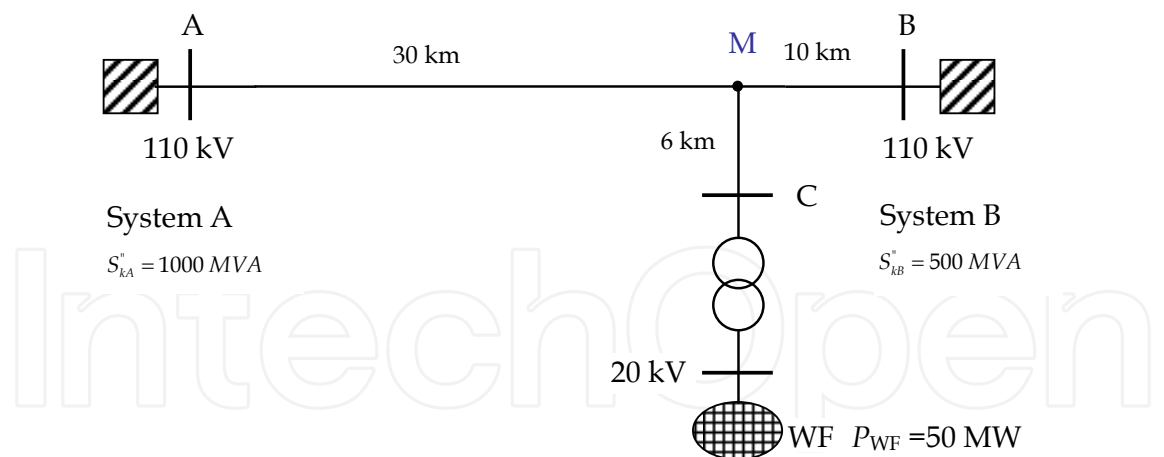


Fig. 19. Network scheme for the second stage of simulations

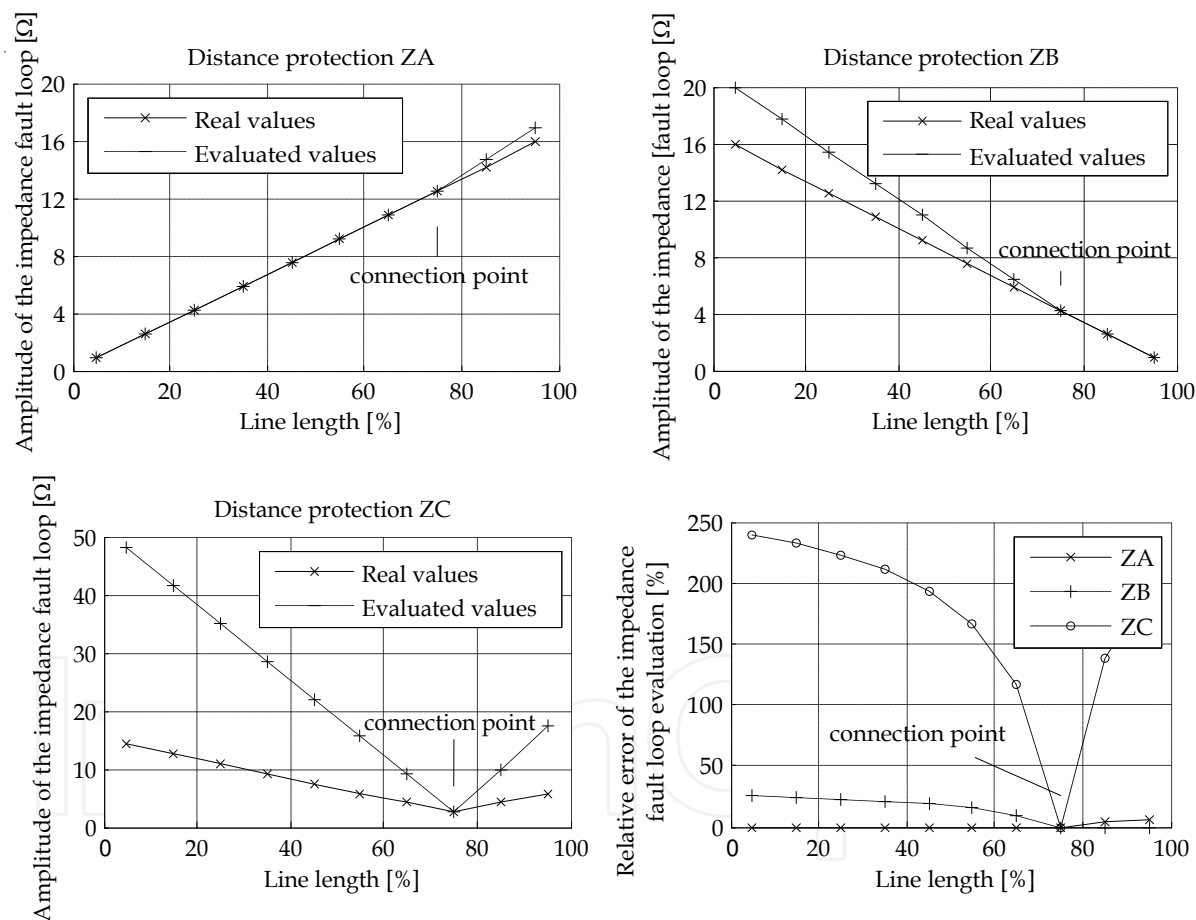


Fig. 20. Divergences between the evaluated and expected values of the amplitude of impedance for protections in substations A, B and C

Analyzing courses in Fig. 20, it can be observed that the highest inaccuracy in the amplitude of impedance evaluation concerns protections in substation C. The divergences between evaluated and expected values are rising along with the distance from the measuring point to the location of fault. It is characteristic that in substations A and B these divergences are at least one class lower than for substation C. This is the consequence of a significant

disproportion of the short-circuit powers of systems A and B in relation to the nominal power of WF.

On the other hand, for the fault in the C-M segment of line the evaluation error of an impedance fault loop is rising for distance protections in substations A and B. For distance protection in substation B a relative error is 53 % at fault point located 4 km from the busbars of substation C. For distance of 2 km from station C the error exceeds 86 % of the real impedance to the location of a fault (Lubošny, 2003).

Example 2

The network as in Figure 17 is operating with variable generating power of WF from 100 % to 10 % of the nominal power. The connection point is at 10 % of the line L_{A-B} length. A simulated fault is located at 90 % of the L_{A-B} length.

Table 3 shows the initial fault currents and error levels of estimated impedance components of distance protections in stations A and C. Changes of WF generating power P_{WF} influence the miscalculations both for protections in station A and C. However, what is essential is the level of error. For protection in station A the maximum error level is 20 % and can be corrected by the modification of reactance setting by 2 Ω (when the reactance of the line L_{AB} is 12 Ω). This error is dropping with the lowering of the WF generated power (Table 3).

WF power		I''_{kA}	I''_{kC}	$\delta_{R(A)\%}$	$\delta_{X(A)\%}$	$\delta_{R(C)\%}$	$\delta_{X(C)\%}$
P_{WF}	$\%P_{WFN}$						
[MW]	[%]	[kA]	[%]	[%]	[%]	[%]	[%]
60	100	2.362	0.481	18.101	18.101	453.286	453.286
54	90	2.374	0.453	16.962	16.962	483.749	483.749
48	80	2.386	0.422	15.721	15.721	521.910	521.910
42	70	2.401	0.388	14.364	14.364	571.213	571.213
36	60	2.416	0.35	12.877	12.877	637.187	637.187
30	50	2.433	0.308	11.253	11.253	729.171	729.171
24	40	2.454	0.261	9.454	9.454	867.905	867.905
18	30	2.474	0.208	7.473	7.473	1097.929	1097.929
12	20	2.499	0.148	5.264	5.264	1558.628	1558.628
6	10	2.527	0.079	2.779	2.779	2952.678	2952.678

Table 3. Initial fault currents and relative error levels of impedance estimation for protections in substations A and C in relation to the WF generated power

For protection in substation C the error level is rising with the lowering of WF generated power. Moreover the level of this error is several times higher than for protection in station A. The impedance correction should be $\Delta R=92.124 \Omega$ and $\Delta X=307.078 \Omega$. For the impedance of L_{CB} segment $\underline{Z}_{LCB}=(3.48+j11.6) \Omega$ such correction is practically impossible. With this correction the impedance reach of operating characteristics of distance protections in substation C will be deeply in systems A and B. Figure 21 shows the course of error level of estimated resistance and reactance in protections located in the substations A and C in relation to the WF generated power.

When the duration of a fault is so long that the control units of WF are coming into action, the error level of impedance components evaluation for protections in the station C is still rising. This is the consequence of the reduction of WF participation in the total fault current.

Figure 22 shows the change of the quotient of steady fault currents flowing from substations A and C in relation to WF generated power P_{WF} .

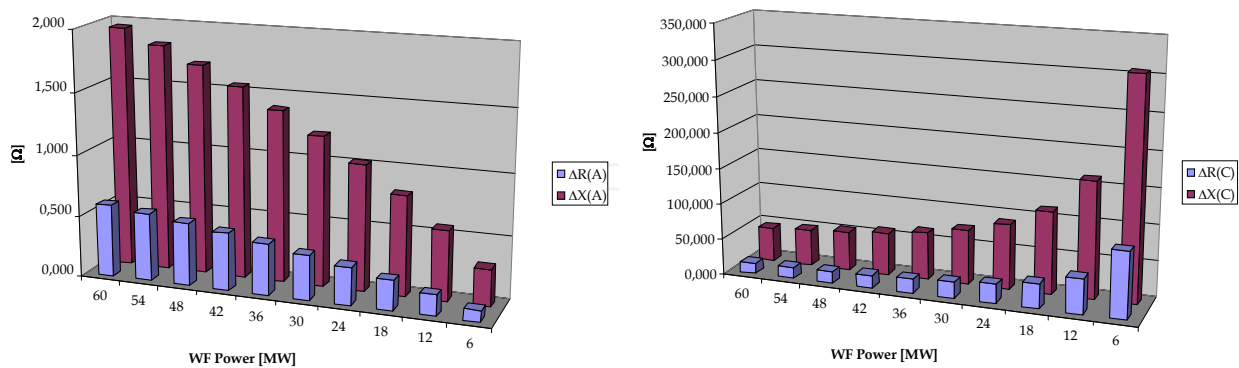


Fig. 21. Impedance components estimation errors in relation to WF generated power for protections a) in substation A, b) in substation C

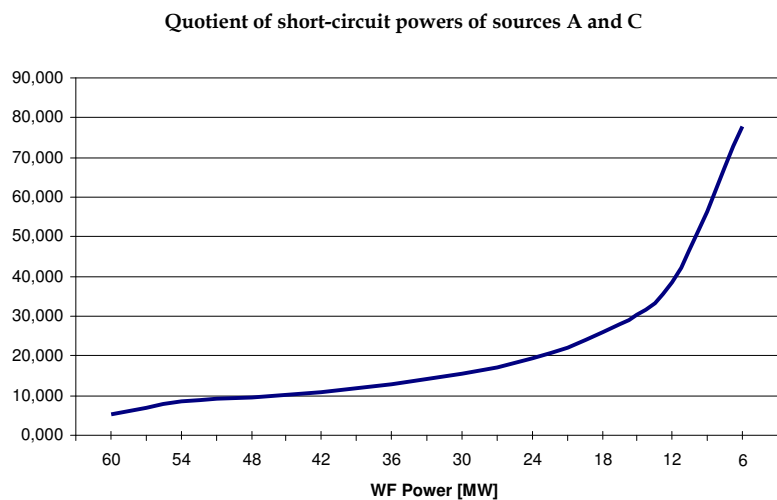


Fig. 22. Change of the quotient of steady fault currents flowing from sources B and C in relation of WF generated power

Example 3

Once again the network is operating as in Figure 17. There are quasi-steady conditions, WF is generating the nominal power of 60 MW, the fault point is at 90 % of the LA-B length. The changing parameter is the location of WF connection point. It is changing from 3 to 24 km from substation A.

Also for these conditions a higher influence of WF connection point location on the proper functioning of power protections can be observed in substation C than in substations A and B. The further the connection point is away from substation A, the lower are the error levels of estimated impedance components in substations A and C. It is the consequence of the rise of WF participation in the initial fault current (Table 4). The error levels for protections in substation A are almost together, whereas in substation C they are many times lower than in the case of a change in the WF generated power. If the fault time is so long that the

control units of WF will come into action, limiting the WF fault current, the error level for protections in substation C will rise more. This is due to the quotient $I_{A(u)}/I_{C(u)}$ which is leading to the rise of estimation error $\underline{\Delta Z}_{(C)} = \underline{Z}_{MF} \frac{I_{A(u)}}{I_{C(u)}}$.

Figure 23 shows the course of error of reactance estimation for the initial and steady fault current for impedances evaluated by the algorithms implemented in protection in substation C.

WF connection point location	I_A	I_C	I_C/I_A	I_A/I_C	$\Delta R_{(A)}$	$\Delta X_{(A)}$	$\Delta R_{(C)}$	$\Delta X_{(C)}$
[km]	[kA]	[kA]	[-]	[-]	[Ω]	[Ω]	[Ω]	[Ω]
3	2.362	0.481	0.204	4.911	0.586	1.955	14.143	47.142
6	2.371	0.525	0.221	4.516	0.558	1.860	11.381	37.936
9	2.385	0.57	0.239	4.184	0.516	1.721	9.038	30.126
12	2.402	0.617	0.257	3.893	0.462	1.541	7.007	23.358
15	2.424	0.6652	0.274	3.644	0.395	1.317	5.247	17.491
18	2.45	0.716	0.292	3.422	0.316	1.052	3.696	12.318
21	2.48	0.769	0.310	3.225	0.223	0.744	2.322	7.740
24	2.518	0.825	0.328	3.052	0.118	0.393	1.099	3.663

Table 4. Values and quotients of the initial fault currents flowing from sources A and C, and the error levels of impedance components estimation in relation to the WF connection point location

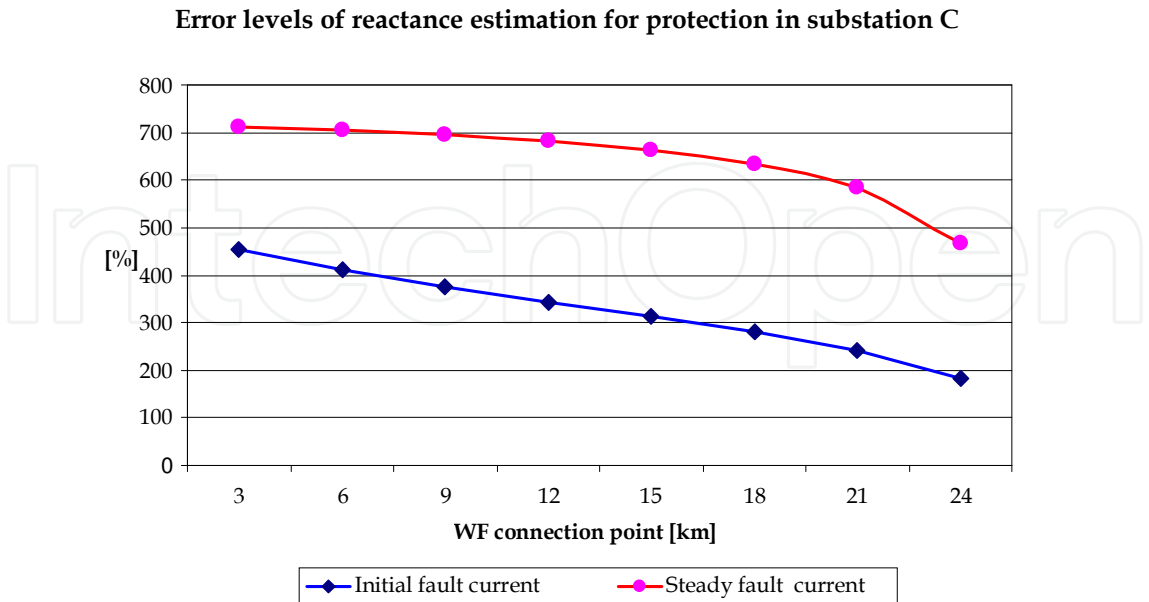


Fig. 23. Error level of the reactance estimation for distance protection in substation C in relation of WF connection point

Taking the network structure shown in Fig. 24, according to distance protection principles, the reach of the first zone should be set at 90 % of the protected line length. But in this case, if the first zone is not to reach the busbars of the surrounding substations, the maximum reactance settings should not exceed:

$$\text{For distance protection in substation A: } X_{1A} < (1.2 + 0.8) = 2 \, \Omega$$

$$\text{For distance protection in substation B: } X_{1B} < (10.8 + 0.8) = 11.6 \, \Omega$$

$$\text{For distance protection in substation C: } X_{1C} < (1.2 + 0.8) = 2 \, \Omega$$

With these settings most of the faults on segment L_{MB} will not be switched off with the self-time of the first zone of protection in substation A. This leads to the following switching-off sequence. The protection in substation B will switch off the fault immediately. The network will operate in configuration with two sources A and C. If the fault has to be switched off with the time Δt , the reaches of second zones of protections in substations A and C have to include the fault location. So their reach must extend deeply into the system A and the WF structure. Such a solution will produce serious problems with the selectivity of functioning of power protection automation.

Taking advantage of the in-feed factor k_{if} also leads to a significant extension of these zones, especially for protection in substation C. Due to the highly changeable value of this factor in relation to the WF generated power and the location of connection, what will be efficient is only adaptive modified settings, according to the operating conditions identified in real time.

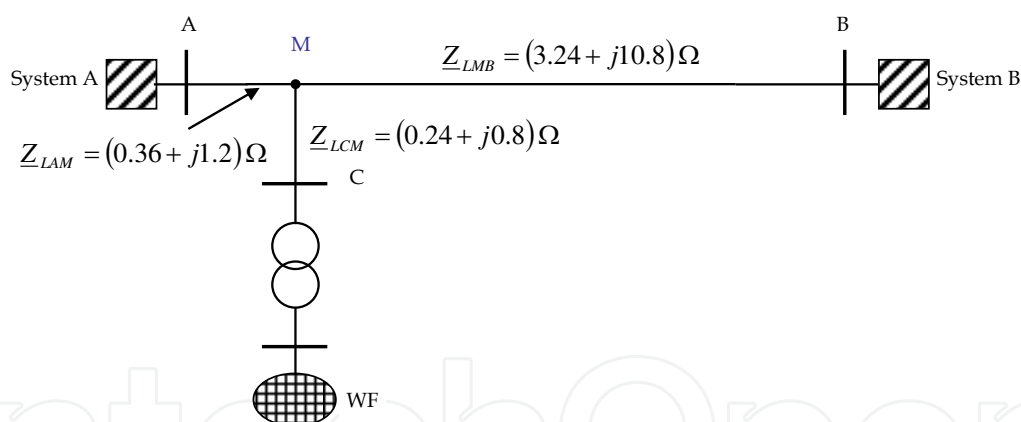


Fig. 24. Simplified impedance scheme of the network structure from the Figure 17

6. Conclusions

The presented selected factors influencing the estimation of impedance components in digital protections, necessitate working out new protection structures. These must have strong adaptive abilities and the possibility of identification, in real time, of an actual operating state (both configuration of interconnections and parameters of work) of the network structure. The presented simulations confirm that the classic parameterization of distance protections, even the one taking into account the in-feed factor k_{if} does not yield effective and selective fault eliminations.

Nowadays distance protections have individual settings for the resistance and reactance reaches. Thus the approach of the resistance reach and admitted load area have to be taken

into consideration. Resistance reach should include faults with an arc and of high resistances. This is at odds with the common trend of using high temperature low sag conductors and the thermal line rating, which of course extends the impedance area of admitted loads. As it has been shown, also the time of fault elimination is the problem for distance protections in substations in the WF surrounding, when this time is so long that the WF fault current is close to their nominal current value.

Simulation results prove that the three-terminal line type of DPGS connection, especially wind farms, to the distribution network contributes to the significant shortening of the reaches of distance protections. The consequences are:

- extension of fault elimination time (switching off will be done with the time of the second zone instead of the self-time first zone),
- incorrectness of autoreclosure automation functioning (e.g. when in the case of shortening of reaches the extended zones will not include the full length of line),
- no reaction of protections in situations when there is a fault in the protected area (missing action of protection) or delayed cascaded actions of protections.

A number of factors influencing the settings of distance protections, with the presence of wind farms, causes that using these protections is insufficient even with pilot lines. So new solutions should be worked out. One of them is the adaptive area automation system. It should use the synchrophasors technique which can evaluate the state estimator of the local network, and, in consequence, activates the adapted settings of impedance algorithms to the changing conditions. Due to the self-time of the first zones (immediate operation) there is a need for operation also in the area of individual substations. Thus, it is necessary to work out action schemes in the case of losing communication within the dispersed automation structure.

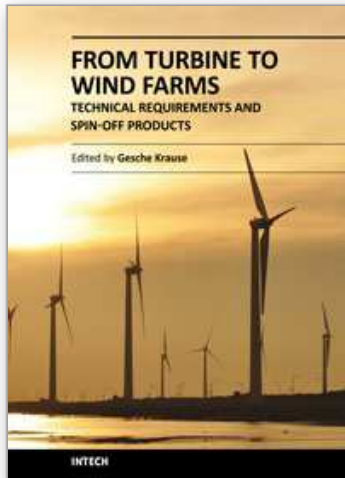
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This book is a timely compilation of the different aspects of wind energy power systems. It combines several scientific disciplines to cover the multi-dimensional aspects of this yet young emerging research field. It brings together findings from natural and social science and especially from the extensive field of numerical modelling.

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Unit 405, Office Block, Hotel Equatorial Shanghai
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Phone: +86-21-62489820
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