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Smart Protection for Enhancement of Stability Conditions of Distributed Generators

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Introduction

Stability is one of the most important features of reliable and secure power system operation. Transient stability is a system ability to return to the initial regime or regime close to the initial after large disturbances. There are lot of turbo generators and hydro generators operating parallel in electric power systems starting from hundreds kW to thousands MW.

Many low power generators are installed in the distribution network. Such phenomenon, called distributed generation (DG), changes power flow direction in distribution network. So, the network with one power flow direction becomes bidirectional power flow network. Despite the many other modernizations, the protection coordination should be adopted to the new network situation as well.

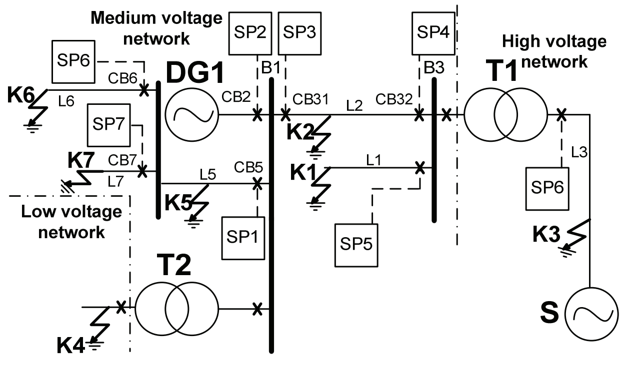

Fig. 1. Medium voltage network with distributed generation

The 5.4 MW distributed generator DG1 is connected to distributed network busbar B1. The distributed network is connected to transmission network S through transformer T1 and overhead line L3 as depicted in Fig. 1. The distributed generator most severe operating conditions were investigated to determined critical fault clearing time of generator synchronous operation during the fault. Also as the electrical distance of synchronous operation of generator were calculated for the fault duration of 1 s. The smart protection (SP) goals could be described as:

1. Decrease overall fault switching time, to decrease heat $I^2 \cdot t$ during the fault;
2. The transmission network protections could satisfy the requirements for generation at distribution network; however the protections should be simplified to reduce its costs.

The model of distributed generator

The turbine-generator unit is described by generator, turbine regulator and exciter models [1]. The generator is synchronous and has two pair of poles [2]. The generator is described by d and q axis circuits.

The generator parameters are described in Table 1.

Table 1. Generator parameters

T'_{do}	T''_{do}	T'_{qo}	T''_{qo}
4.409	0.043	0.1	0.043
H	D	X_{d}	X_{q}
3	0	2.413	2.292
X'_{d}	X'_{q}	X''_{d}	X_{l}
0.166	0.556	0.136	0.096
$S(1.0)$	$S(1.2)$		
0.14	0.7		

The turbine was modeled using enough detailed steam turbine model TGOV5 [2]. This model can simulate the parameters of a boiler. Due to that, there is a possibility to investigate a long term transitional operation.

Generator excitation parameters are listed in Table 2.

Table 2. Generator exciter parameters

T_{R}	K_{P}	K_{I}	K_{D}
0.005	0.905	0.725	0.35
T_{D}	K_{A}	T_{A}	V_{RMAX}
0.04	1	0	5

V_{RMIN}	T_E	K_E	E_1
-5	0.47	1	0
$SE(E_1)$	E_2	$SE(E_2)$	-
0	1	0.256	-

The excitation system of generator is the digital system which working PID regulation. Excitation system is designed as dynamic model of digital excitation system ESAC8B which allows change the principle of regulation [2].

The critical time evaluation

The first part of this investigation is to find the longest time duration for synchronous operation of generator through three phase faults. The results have showed that generator is stable for 0.25 s and unstable for the fault duration 0.3 s. There was found critical time duration of 0.26 s for stable and synchronous operation of generator. Generator operates in unstable zone and does several asynchronous revolutions on 0.27 s. The oscillations of rotor angle are depicted in Fig. 2.

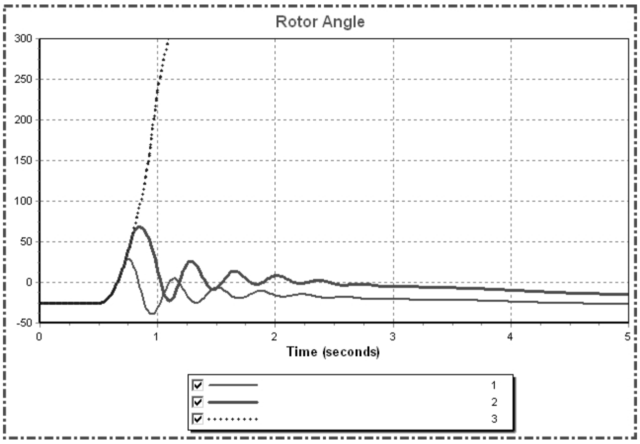

Fig. 2. The generator rotor angle dependence on fault clearness time: 1 - $t = 0.2\,\text{s}$; 2 - $t = 0.26\,\text{s}$; 3 - $t = 0.3\,\text{s}$

So the calculated critical fault clearness time of 5.4 MW distributed generator is 0.26 s.

The maximum electrical distance evaluation

If the fault occurs in point K1 (Fig. 1) the DG stability depends on impedance from DG to fault. However, the inertia time constant and inertia moment are small of such low power DG, and leads to small critical (till fault clearing) time as shown previous. However, the typical fault clearing values in distribution network could reach 1.0 - 2.0 s.

The electrical distance between generator and fault location were investigated for the three phase fault duration of 1 s.

It was assumed that 5.4 MW generator is connected to the large electric power system, not less than 250 MVA. The fault was modeled at point K3 Fig. 1. The calculation have shown that the distributed generator loss its synchronism. The critical fault clearness time is 0.4 s.

The calculated electrical distance from generator to the fault is about $0.918\,\Omega$ at $10\,\text{kV}$ side for the fault clearing time of 1 s.

Conventional protection coordination

The distribution network specific is the long fault clearness time. The overcurrent protection second and first stages settings could reach 1.0 – 2.0 s. At the time longer than critical fault clearness time, the generator loss the synchronous mode, and probably would be disconnected from network due to frequency or asynchronous mode detection protection. The generator disconnection from the system could lead to the loss of boiler, and finally loss of the generating unit. Such loss of the unit is undesirable and some automation should be implemented.

It is worth to mention, that some of turbine vendors are implemented fast turbine valve control algorithm. That algorithm could close valve with time delay of about 80 ms and the valve full close time of about 400 ms. Of course the valve motion is not linear.

Further on study has shown that even though the turbine power decreases towards zeros per 400 ms during the fault, the generator loss its synchronism. So the specialized limitation of turbine steam during the near fault does not improve generator dynamic stability for prefault generator power of more than 1 MW. The specialized turbine steam limitation could lead to generator dynamic stability for the generator distance to the fault of $0.918\,\Omega$, for the regime of nominal generator prefault power and 1 MW post fault auxiliary power. The fault point K3 (Fig. 1) assume distance to the fault of $0.918\,\Omega$.

Finally, only immediate generator disconnection from network and decrease of turbine power could lead to retention of the unit of boiler, turbine and generator. The generator could be synchronized successfully back to the grid after the fault clearing.

The conventional protection coordination does not allow reduce protection without reduce protection selectivity, sensitivity. This mean that some transmission network protection attributes should be used in distribution network. However, transmission network protection costs increase the costs of setup of distribution generation. The smart protection should be applied to distribution network to reach required protection selectivity, sensitivity, fast working.

Smart protection coordination

Network elements, such as transformers or generators acts as capacitance load for travelling wave for the frequency range $100 \div 1000\,\text{kHz}$. SP contrary to conventional protection are isolated in the medium voltage network [3–8], as it is depicted in Fig. 1.

After suppression of processes classified as first travelling wave, the charges distribution processes begins in the distributed network. The distribution of charges induces currents and changes the phase voltages. Different shape currents flows left and right side from fault place.

If the fault occurs at the point K2, the current shape measured by SP4 depends on parameters of the part of the network connected to bus bars B3 and includes line L2 with the distance to the fault place L_{2X} . So, the total network length, measured by SP4 for fault place K2, is $L_{2X} = L_{2MEAS} - L_1$. The distance L_1 represents the known total network length in reverse direction of SP4 i. e. $L_{SP4\,REV}$.

The same principle could be applied for SP5 and fault place K5

$$L_{1X} = L_{MEAS} - (L_2 + L_5 + L_6 + L_7) = \\ = L_{MEAS} - L_{SP5\,REV}. \qquad (1)$$

So, if $L_{1X} \le L_{1Def}$ the calculated line length during the fault (1) is less than SP5 defined line length L_{1Def} SP trips with in time delay t_0 as depicted in Fig. 3.

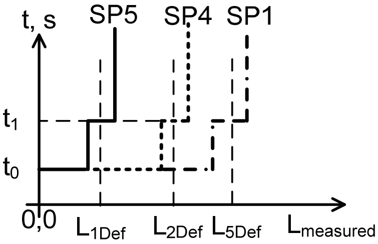

Fig. 3. The smart protection SP5, SP4 and SP1 coordination

Special cases should be discussed for the travelling wave based protection coordination.

SP4 and SP1 coordination for fault place K5. The SP1 detects travelling wave earlier than SP4. However this difference is quite small comparing with CB's commutation time and depends on line length. The distance to the fault $L_{2X} > L_{2Def}$ measured by SP4 is higher than defined line length L_{2Def} and SP4 do not trip as depicted in Fig. 3. The SP1 calculates distance to the fault as described above

$$L_{5X} = L_{MEAS} - L_{SP1\,REV}. \qquad (2)$$

If the calculated line length value L_{5X} is less than SP1 defined value L_{5Def} the SP1 trips with in time delay t_0 as depicted in Fig. 3. The SP3 do not detect fault, because the fault direction is opposite, than defined in SP. It is obvious, that coordination of SP's do not requires additional time delay as it is common for the conventional protections. So, the travelling wave based SP's time to mechanical switch off depends on algorithm calculation, auxiliary relays and CB mechanical trip delays.

The fault K5 is close to bus bar B1. The cable line, even though overhead line length could not be known with 100 % confidence: wire length due to temperature variation changes the real line length; the ice on overhead line wire and corona effects changes the speed of travelling wave. All these conditions make influence on reliability of travelling wave based protections.

Transmission network distance protection coordination principle could be applied. Two stages SP should be used for SP4. The first stage secures 70 % of the line L2 with no time delay. The second stage secures 110 % of the line L2, i. e. overlaps line L2 and has some additional time delay according to medium voltage network protection coordination.

Both SP3 and SP4 would have the same defined line length L_{2Def} and margins

$$L_{2Def} - \Delta L_1 \le L_{2Def} \le L_{2Def} + \Delta L_2 . \qquad (3)$$

The SP3 and SP4 protection coordination diagram is depicted in Fig. 4.

Stability of DG1. If the fault occurs in the low voltage network, for example place K4, the impedance between DG1 and fault place is enough high and the fault clearness time increases. However, SP in the medium voltage side do not act due to insulation of travelling wave from low voltage side.

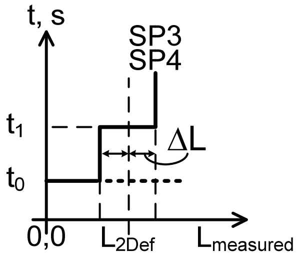

Fig. 4. The smart protection SP3 and SP4 coordination

The stability of distributed generator DG1 mainly depends on fault clearness time as it was discussed above. The medium voltage network protections detected "forward direction" starts practically at the same time; however the trip would be initiated only by the nearest to fault SP. The SP coordination allows reduce mechanical CB's switch off delay to the values of $50 \div 100$ ms. The value of 50 ms could be used for the first stage of SP, also 100 ms could be used for the second stage.

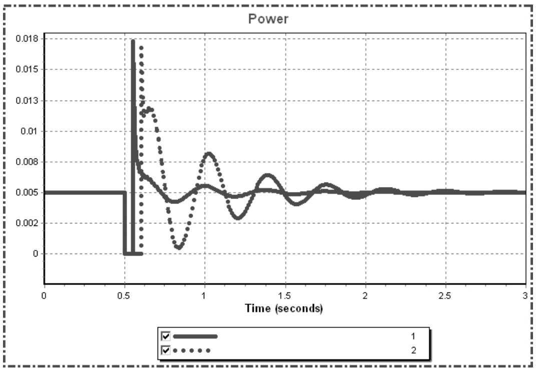

Fig. 5. DG1 power output before, during and post fault in relative units. Fault clearness time: 1 – 0.05 s; 2 – 0.1 s

The stability calculations of DG1 yields that even though fault reactance is zero, generator remains stable for the fault clearness time 0.05 s or 0.1 s. Generator output power equal to nominal power for the prefault and postfault calculations. The system reactance before and after the fault left not changed. The DG1 output power and rotor angle during the fault are depicted in Fig. 5 and 6.

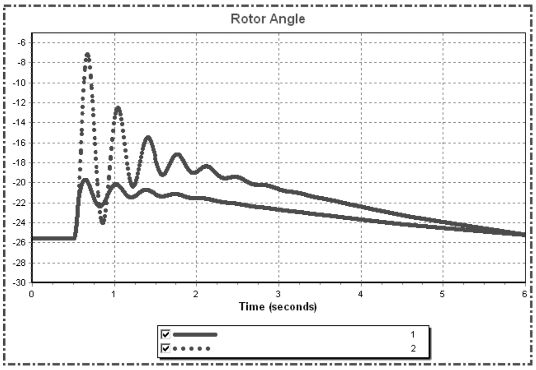

Fig. 6. DG1 rotor angle before, during and post fault. Fault clearness time: 1 – 0.05 s; 2 – 0.1 s

The generator power is shown in per units, which could be recalculated to the MW units using factor of 1000.

Conclusions

1. The generator could not satisfy dynamic stability conditions in the grid due to high fault clearness time in the grid and small unit inertia time constant.
2. The requirement to keep the unit as much as possible longer connected to the grid during the external fault could be fulfilled only by special protection.
3. The switching off of steam supply to turbine per 400 ms from the start of fault guaranty retain of the unit only for faults point in the transmission network.
4. The usage of smart protections simplifies protection coordination in the medium voltage network and reduces fault clearing times to the values secure to stability of dispersed generators.
5. The smart protection reliability could be increased by usage of multiple protection stages.

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The transient stability of the dispersed generator were investigated. Generator is connected to the distribution network. The concept of smart protection is proposed. The smart protection coordination during the fault conditions was investigated. The dispersed generator transient stability with smart protection was investigated. The recommendations for generator protection coordination according to stability requirements are made. The investigation has showed, that the smart protections greatly increase generators stability margins. Ill. 6, bibl. 8, tabl. 2 (in English; abstracts in English and Lithuanian).

V. Šiožinys, A. Baranauskas. Paskirstytosios generacijos generatorių stabilumo atsargos padidinimas išmaniosiomis tinklo apsaugomis // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 1(117). – P. 71–74.

Tiriamas paskirstytosios generacijos generatoriaus stabilumas ir stabilumo sąlygos. Generatorius prijungtas prie skirstomojo tinklo. Pasiūlyta išmaniųjų apsaugų struktūra skirstomajam tinklui. Ištirtos išmaniųjų apsaugų koordinavimo sąlygos tinklui veikiant įvairiais avariniais režimais. Ištirtas paskirstytosios generacijos generatorių stabilumas, kai tinkle įdiegtos išmaniosios apsaugos. Pateiktos rekomendacijos, kaip koordinuoti išmaniąsias apsaugas, atsižvelgiant į paskirstytosios generacijos generatorių stabilumo sąlygas. Tyrimo rezultatai parodė, kad išmaniosios tinklo apsaugos gerokai padidina paskirstytosios generacijos generatorių stabilumo atsargą. Il. 6, bibl. 8, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).