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The new power based approach in pole slip protection

Abstract. The paper presents a new method of pole slipping protection which eliminates the need for complicated calculations of setting, thus greatly simplifies the setting process. The new adaptive algorithm uses machine's powers measurements to ascertain whether the synchronous machine is committed to a pole slip. The main efforts have been focused on the development of new protection techniques, which should ensure better (faster and more selective) detection of synchronous machine loss of synchronism. It can operate successfully using results from simulation, as well as from laboratory tests of real synchronous machines.

*Streszczenie. W artykule zaprezentowano nową metodę przeciwko poślizgowi biegunów, która w znaczący sposób upraszcza dobór nastaw zabezpieczenia przez eliminacje procesu skomplikowanych obliczeń. Dzięki adaptacyjności metody zarówno dla trybu pracy generatorowego jak i silnikowego można skutecznie określić, czy w maszynie synchronicznej wystąpił poślizg biegunów. W artykule przedstawiono szybką i selektywną metodę detekcji poślizgu, której działanie zostało sprawdzone zarówno podczas badań symulacyjnych jak i z wykorzystaniem rzeczywistych sygnałów testowych. (**Podejście mocowe w zabezpieczeniu przeciwko poślizgowi biegunów**)*

Słowa kluczowe: poślizg biegunów, Zabezpieczenie przed poślizgiem biegunów, kryterium równości pól, samonastawne zabezpieczenie przed poślizgiem biegunów

Keywords: Pole Slip, Pole Slipping Protection, Extended Equal Area Criterion, Self Tuning Pole Slip Protection.

Introduction

In transmission systems the probability of pole slipping on main generators is very low, because the criteria have become more stringent over last decades. Present trend of connecting small and medium sized synchronous generators that are operating parallel with the utility grid puts such machines in a potentially damaging situation. An increasing amount of embedded generation connection to sub-transmission and distribution power system caused new interest in pole slipping protection that earlier was not provided on these machines. Pole slipping can arise due to external disturbances such as long fault clearance time, faulty excitation a loss of excitation, or an excess of prime mover input power caused by a sudden and large loss of load. It can result in serious problems such as severe pulsating torques produced during pole slipping that can torsionally excite the section of the shaft and expose them to oscillatory stress.

Pole slipping of a synchronous machine occurs during insufficient electromagnetic torque to hold the rotor in synchronism with the stator magnetic flux [1]. It is caused by an imbalance between the mechanical power and electrical power of a synchronous machine. Pole slipping either between generators and systems, or between two sections of the systems, results in a flow of synchronizing power, which reverses in direction twice every slip cycle.

Pole slipping of any size of synchronous machine will always cause problems and when machine pole slips is required to disconnect it from the utility grid as soon as possible, thus prevent the generator against possible damage [2]. This condition causes high currents and impact on the generator windings, and high levels of transient shaft torque.

Industrial and small generators should be quickly tripped when irrecoverable slipping internal angle occurs at their end. Large system generators sustain network stability and their tripping is integrated in a defense plan of the power network. Pole slipping protection is required when generator looses synchronism with the utility's main source of power and is subjected to high fluctuations in the current that passes through it.

Pole Slip Protection Techniques

Pole slipping can be easily observed by measuring directly the load angle in the synchronous machine but that approach requires additional sensors and devices. There are known methods that protect the machine against the danger of the pole slip without such devices.

The classical methods for detecting pole slipping examine the variation in the apparent impedance of a generator as seen from its terminals and are based on distance type relays that use a combination of MHO and linear characteristics as described by Imhof *et all* [1].

Pole Slip protection requirements, in general, are:

- *Reliable detection of the first and subsequent pole-slips for both generating and pumping modes of operation*
- *Detection of pole-slip rates within the range 0.1% to 10%*
- *Discrimination between pole-slips occurring with a system centre within the machine impedance and the windings of its step-up transformer (stage 1), and pole-slips occurring with a system centre beyond the transformer HV terminals (stage 2)*

The variation of impedance seen at the generator during pole slipping is shown on Fig.1. The trip signal is sent if the measured impedance crosses two characteristics on an impedance plane within a specified time limit.
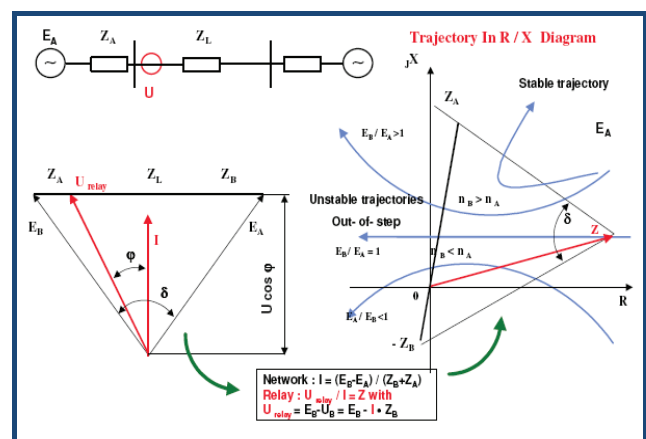

Fig. 1 The two machines model with its voltage vectors and Z plane that shows impedance loci measured by relay [3]

Different types and shapes of characteristics can be applied to increase the protection selectivity, such as one or two blinders, MHO or a lenticular characteristic presented in Fig 2. The MHO scheme is susceptible to mal-operations

during stable swings if the characteristic is set too large. It is also possible to fail to detect some pole slips, if time delays are used in order to prevent nuisance tripping during stable swings [4].

The single blinder scheme is the most secure of the conventional schemes, but the price for this extra security against relay mal-operation is that a complete pole slip cycle is required for the scheme to operate.

The double blinder characteristic is less secure than the single blinder scheme, and may fail to detect the first pole slip following a fault close to the machine. Like the single blinder scheme, it requires a complete pole slip cycle to operate properly.
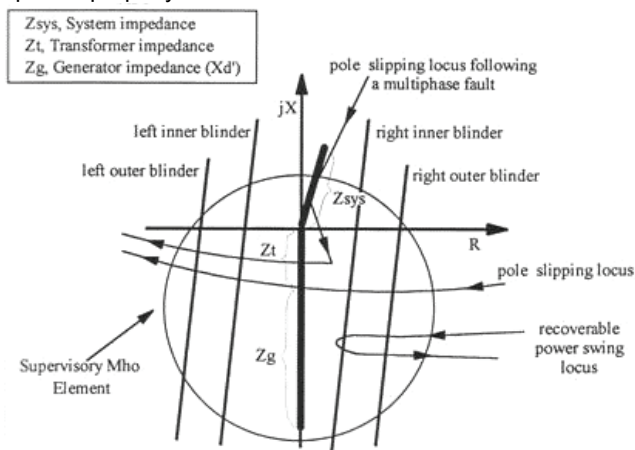

Fig. 2 The MHO characteristic with double blinder pole slip protection

Self Tuning Pole Slip Protection

The new method is called Self Tuning Pole Slip Protection (STPSP). It is the power based method that makes use of the observation of active and reactive power on the protected machine connected to the grid. The name indicates method's fundamental feature – adaptability of tripping settings. A method that allows for precise and selective protection of the machine against pole slipping should contain many different tripping settings of algorithms or adaptive settings for one working algorithm. Because, from the customer's point of view, it is always better to have as few settings as possible, the ones directly deciding about protection tripping are calculated separately for every sample of data.

The STPSP has it origin in Equal Area Criterion (EAC) [2] and Extended Equal Area Criterion (EEAC) approach [4]. The STPSP monitors directly the values of active power P and reactive power Q. The new method determines whether the energetic state of the machine may cause the Pole Slip phenomenon. However, there are significant changes in comparison to EAC and EEAC approaches. First of all, the method finds the operating point of the machine by itself and can easily determine the value of active power where synchronism is lost. The second, and the most significant, change is that the trip level of reactive power Q is not set once for the entire run of the machine. The STPSP calculates different reactive power trip levels for each data sample. This improvement is caused by the fact that different types of disturbances have a different impact on the reactive power. Thirdly, there is an extension in method of finding the disturbance – it improved calculation of operating point of the machine. This allowed to detect more types of disturbances with better selectivity and efficiency. Moreover, differently to other known methods, derivative calculation operation is not used in final

criteria calculation, which is always a numerical issue. The new solution can be applied for the synchronous generator and motor as well. All of it takes advantage of algorithm selectivity and efficiency.

The idea of the STPSP algorithm has been presented in Fig. 3. Firstly (step S1), algorithm reads setting parameters: especially longitudinal synchronous reactance X_d, the mode of operation of the machine (generator or motor), the insensitivity zone for small power swings, allowed slipping time, sampling frequency. Then (step S2), algorithm reads measured values of current and voltages at machine terminals. In step S3 algorithm utilizing current and voltages sampled values calculates the values of active power P and reactive power Q and calculates the average value of voltage for all three phases. The method calculates also average active power for determining the operating point of the machine – the active power before disturbance.
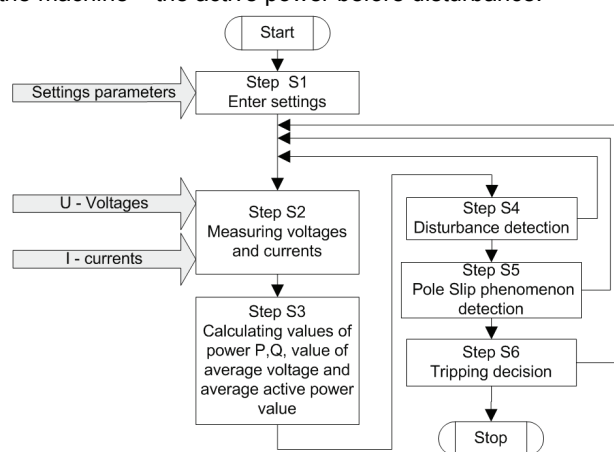

Fig. 3 The STSPS – simplified algorithm's diagram

In step (S4) the STPSP method looks for disturbance that might cause pole. Because pole slipping is the power-based phenomenon it is enough to monitor changes in time of active power values. The observation is sensitive for two types of changes of active power:
a) sudden changes of active power – will happen during faults, short circuits, voltage sags; these changes are monitored by checking if active power crossed its own envelope calculated with use of insensitivity zone and average power;
b) long time changes of active power – will happen during increasing overloading, a loss of excitation; these changes are monitored by checking how much active power has changed in certain time (typically 1s, 5s, 15s, which depends on the machine).

After disturbance has been found the method is looking for the effects of disturbance – pole slip phenomenon occurrence (step S5). Pole slip can occur at certain values of active and reactive power. Thus, the values of P tripping and Q tripping are calculated. For active power pole slipping occurs when current active power is lower than active power before disturbance, for reactive power tripping conditions are calculated utilizing longitudinal synchronous reactance and voltages.

During the investigation of pole slipping phenomenon also the influence of first pole slipping on the synchronous machine has been considered. It occurs that for synchronous machine to operate for some time in a loss of synchronism (e.g. during start-up or pulling into step) is not a danger. It results in the statement that pole slip protection function needs to find the first pole slip, but in many cases it

is not necessary to trip directly after the first slip. Pole slipping can induce thermal stress on insulation, etc. so the real danger from pole slipping is an enormous increase of power in time. It leads to the conclusion that each and every synchronous machine has its own allowed time of work in pole slipping [6] and should be set individually for each application. This time value is one of the settings for the method and trip signal is considered only after allowed slipping time. So the described STPSP method at step S6 calculates two binary outputs:

- PSPA2_warning – indicates/informs that the energetic state of the machine point to pole slipping; this is the estimation of the first pole slip;

- PSPA2_trip – indicates that after allowed time of save pole slipping (to set up during algorithm configuration) another pole slip occurred and the further run of the machine is considered as the risk of damage.

If the tripping decision is negative and the machine comes back to stability, the algorithm can reset values from step S4 to S6 and start over disturbance detection.

The STPSP algorithm basically utilizes two criteria to determine whether the found disturbance causes pole slipping:

$$(1) \quad \begin{cases} (\ P(k) < P_{bef\_latch} \ (for \ motor) \quad OR \\ \\ P(k) > P_{bef\_latch} \ (for \ generator) \ ) \\ \\ AND \\ \\ Q(k) < Q_{trip\_level}(k) \end{cases}$$

where: k – discrete time variable, P – value of active power, P_{bef_latch} – value of active power before disturbance, calculated once on every disturbance, Q – value of reactive power, Q_{trip_level} – tripping value for reactive power calculated dynamically for each sample:

$$(2) \quad Q_{trip\_level}(k) = -\frac{1}{2}(\frac{1}{X_d}) \cdot V_{bef\_latch} \cdot V_{avg}(k)$$

where: X_d – Direct-axis synchronous reactance of protected machine; V_{bef_latch} – value of voltage magnitude before fault,

$$(3) \quad V_{bef\_latch} = V_{avg}(k)\Big|_{k=m-1} \\ _{the \ moment \ of \ disturbance}$$

where: V_{avg} – arithmetic average 3-phase voltage,

Simulation Studies and Test Results

The performance of the STPSP algorithm has been tested using computer simulations and laboratory machines in all common types of disturbances i.e. sudden overloading, increasing overloading, a loss of excitation and voltage collapses. The Simplorer and Simulink programs were used to model the SM machines. Laboratory tests of a real synchronous generator and a synchronous motor have been also performed. Parameters of those machines are presented in the tables below.

Table 1 The parameters of Simplorer model

S_N	3.15 MVA
P_N	2.3 MW
Q_N	2.15 MVar
cosφ	0.73
V_N	6.6 kV
I_N	276 A
f_N	50 Hz
pole pairs (p)	8
n_N	375 rpm

Table 2 The parameters of Simulink model

S_N	3.63 MVA
P_N	3.15 MVA
cosφ	0.9
V_N	6 kV
I_N	350 A
pole pairs (p)	8
n_N	375

Table 3 The parameters of real generator

P_N	9 kW
cosφ	1
V_N	220 V
I_N	23.6 A
f_N	50 Hz
n_N	1000 rpm
V_{fN}	110 V

Table 4 The parameters of real motor

P_N	4 kW
cosφ	0.8
V_N	400 V
I_N	7.2 A
f_N	50 Hz
n_N	3000 rpm

The exemplary runs of the machine were selected and after that STPSP algorithm was executed (in a post-processing mode). Each example contains two figures. In the figure 4a) the upper plot presents active power trip signal, active power, active power envelope (before disturbance) and latched mean active power before disturbance, the lower plot presents reactive power trip signal, reactive power and reactive power trip level. In the figure 4b) the plot presents reference load angle with pole slips, pole slip detection signal, warning signal (first pole slip) and final protection trip signal.

The results are as follows:
Simplorer machine model in motor operating point in the case of reduction of excitation to 0.4 p.u.
This test presents the situation of reduction of excitation in time of 12 seconds. In that case only one pole slip occurred and the algorithm can detect it properly. Prior to the main detection there is some noise in the detection caused by noise in power P and Q signals. In this particular case it can be easily observed that if the allowed slipping time is too short, the final tripping could be set and that kind of protection action could be unnecessary in the case of only one pole slip.
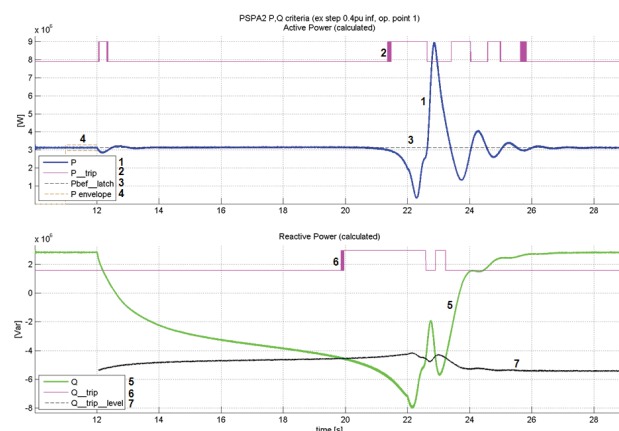

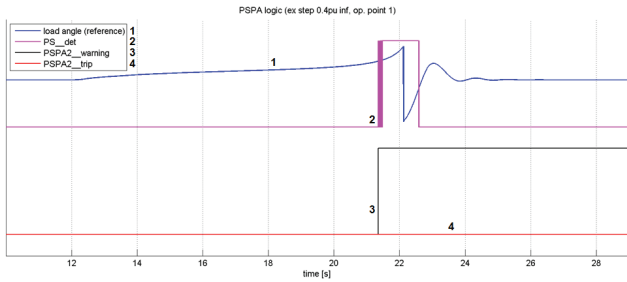Fig. 4 a) Reduction of excitation - active and reactive power

Fig. 4 b) Reduction of excitation – load angle, pole slip detection and tripping at default settings

Simulink machine model in generator operating point in the case of ABC fault with long clearance time 1s.

Figure 5 a) and 5 b) show the situation where three pole slips occur just after the power swing. As it can be noticed, the method recognizes all three slips correctly but is robust for the following power swings. Also in this case only PSPA2_warning flag has been set, because typically 3 slips are allowed for most of the applications.
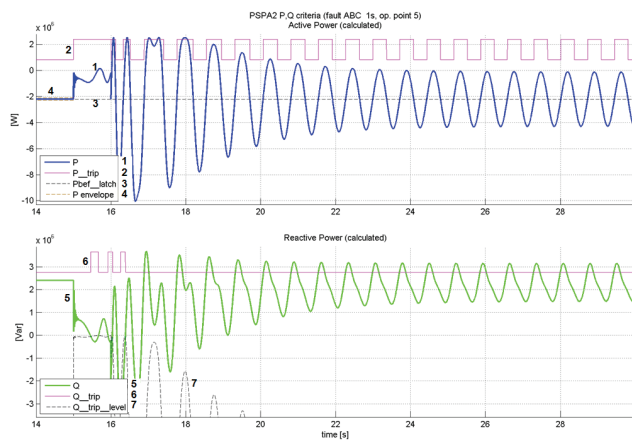

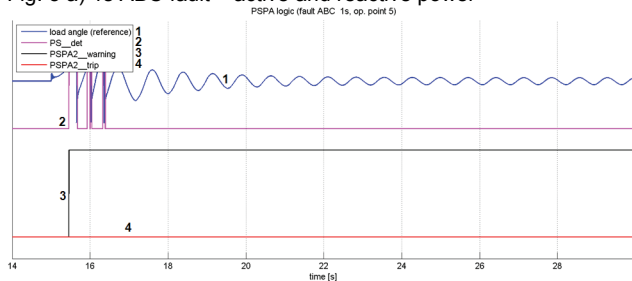Fig. 5 a) 1s ABC fault – active and reactive power

Fig. 5 b) 1s ABC fault – load angle, pole slip detection and tripping at default settings

Laboratory test of synchronous generator during overloading

Fig. 6 a) and 6 b) present the result of the laboratory test of a real generator (Table 4) during its overloading. In the 11th second of the test pole slipping occurred. It is important to mention that the drop of load angle in the 9th second is not a pole slip at all, it is just a result of a slightly wrong estimation of load angle in a steady state (a proper direct estimation of load angle in a real machine is another subject, not considered in the present paper). In this case the protection algorithm starts finding all the pole slips and after 2 seconds of pole slipping the method sets the PSPA2_trip flag to inform that further pole slipping might cause damage to the machine.

The last exemplary result presents the situation of short tripping out of stator voltage. As it can be seen, before the 1st second the machine starts to slip poles and after the 8th second it is turned off.
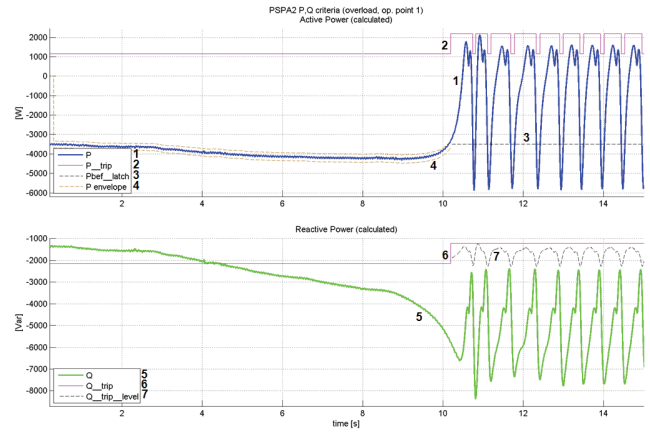

Fig. 6 a) Overloading – active and reactive power with criteria response
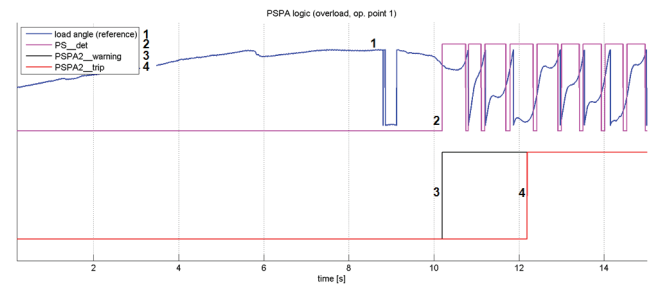

Fig. 6 b) Overloading – load angle, pole slip detection and tripping

Laboratory test of synchronous motor in the case of out of stator voltage

Also in this case the STPSP function can identify the pole slips and trip properly. At first pole slip the PSPA2_warning flag is set, PSPA2_trip occurs after allowed slipping time and, when the slips stop, the algorithm also shows no detection of it.
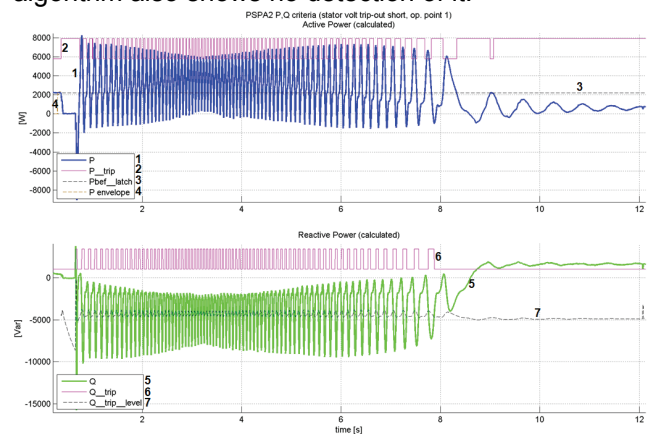

Fig. 7 a) Short tripping out of stator voltage – active and reactive power
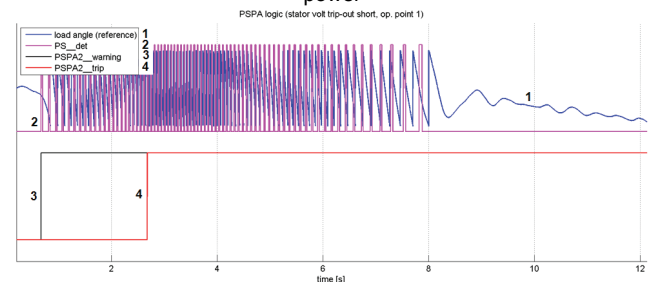

Fig. 7 b) Short tripping out of stator voltage – load angle, pole slip detection warning and trip

Conclusions

The article presents a new method of pole slip protection called STPSP. During simulation and laboratory tests the reliability and efficiency of the method has been proved. The method can work for synchronous generators, as well as motors. The new algorithm can also properly distinguish stable power swings from pole slip condition.

As shown in former paragraphs, the new method is more selective than present-day classical methods, it can handle with various types of disturbances (i.e. sudden overloading, increasing overloading, a loss of excitation and voltage collapses). Another advantage of STPSP algorithm is its usefulness resulting from its adaptive ability to changing conditions of SM operation.

The new STPSP method presented in the article can detect pole slips of synchronous machines separately. It gives the opportunity to set the trip depending on the machine and application. It might be very helpful in case of transient disturbances. Also important is the fact that STPSP algorithm can identify the first pole slip typically about 50-250ms before it occurs depending on the settings (e.g. Fig. 6b). It can be also very helpful in situations where slipping time is not allowed whereas pole slip detection time is crucial for an application.

On the basis of the exemplary results (simulated and laboratory tests) one can conclude that the method based on machine powers observations for detection of pole slipping phenomenon can potentially bring effective solutions in future applications and can be helpful in pole slipping protection of synchronous machines.
In the future, authors plan to run field trials on an industrial synchronous motor and a generator for the small and medium sized synchronous machine application

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