CHARACTERISTICS OF DOUBLY-FED MOTOR-GENERATOR DURING THE FAULT

Valentin AŽBE, Rafael MIHALIČ

POVZETEK

Dvojno napajani motor-generatorji (DFMG) bodo vključeni v slovenske črpalne elektrarne—eden od njih je že v obratovanju—in bodo postali pomemben del slovenskega elektroenergetskega sistema, zato je pomembno poznavanje obratovalnih lastnosti teh strojev. Ta članek predstavlja karakteristike delovanja DFMG med in po kratkem stiku. Med kratkim stikom—ko DFMG obratuje kot asinhronski stroj—pride do nasičenja reaktanc DFMG in v kombinaciji s padcem napetosti bistveno vpliva na električni navor stroja. Razlika med statično in dinamično karakteristiko delovne moči glede na hitrost vrtenja je prikazana z uporabo trajektorij hitrosti rotorja. Poleg tega smo upoštevali različne upornosti zaščite »crow-bar«. Rezultati simulacij kažejo, da ima med kratkim stikom ta upornost velik vpliv—če želimo doseči dobro prehodno stabilnost pri velikih motnjah, mora biti ta upornost primerno izbrana.

ABSTRACT

Doubly-fed motor-generator (DFMG) will be included in pumping-storage plants in Slovenia—one of them is already in operation— and they will become an important part of Slovenian electric-power system, so it is important to know the behavior of these machines. This paper presents the characteristics of a large doubly-fed motor-generator during and after the fault. During the fault—where DFMG operates as an asynchronous machine—the machine meets the saturation and in combination with the network-voltage reduction this largely affect the electrical torque of the machine. The difference between static and dynamic power-to-speed characteristic is presented with the application of trajectories of rotor speeds. Besides various resistances of crow-bar protection were considered. Results of simulations show that during a fault a crow-bar resistance has an important role—in order to increase the transient stability of DFMG, proper value of crow-bar resistance should be applied.

1. INTRODUCTION

Doubly-fed motor-generators (DFMG) with the application of power electronics enables a new principle of control of the active and the reactive power and speed. The control of a DFMG can be—due to the application of power electronics—very rapid, comparable to the control of FACTS devices. In this way a DFMG can be applied for tasks that are typical for

FACTS devices in the field of power-system dynamic, e.g. transient stability improvement. The paper presents one part of transient stability assessment, i.e., the behavior of a DFMG during and after the fault. In this case a DFMG operates as an asynchronous machine due to the activation of a crow-bar protection. Crow-bar protection inserts three-phase resistance in series to the rotor windings.

A technology of a DFMG is—in the field of pump-storage plants —relatively new and with little experiences. That is why the modeling of these devices and the modeling of their controls is not a trivial task and references are few. A majority of simulation programs for dynamic analysis of electric-power systems do not enable direct use of such an element. That is the reason why the understanding of the operation is important for proper modeling of this device for the dynamic studies. Important part of pump-storage plants is also a long pipeline that has a large influence on the dynamic characteristic within some electro-mechanical phenomenon, so proper model of turbine and pipeline should be considered. Considering DFMG in a model of an electric-power system is even more important when DFMGs are relatively big, as it is the case in Slovenian EPS—the nominal power of hydro pumping-storage plants (PSP) incorporating DFMGs will be in the range of 1/4 of installed generating capacity in Slovenia.

Firstly basic operating characteristics of a DFMG are presented. Voltages and currents of the rotor are presented for various operating points. In third chapter the DFMG's behavior during a fault is described and the results of dynamic analyses are shown and the fourth chapter draws conclusions.

2. BASIC PRINCIPLES OF OPERATION OF A DFMG

In this chapter basic principles of DFMG are presented. Rotor of the DFMG is connected to the turbine by the common shaft. Stator is directly connected to the grid, while rotor is connected to the grid via slip-rings and a converter that control the voltage on the rotor and in this way enables the control of active and reactive power. A basic scheme of a DFMG is presented in Fig. 1. The active power over the rotor is approximately equal to:

$$P_{\mathrm{r}} \approx slip * P_s \tag{1}$$

According to (1) in the vicinity of synchronous speed the active power through the converter is small. Generally, a DFMG can generate or consume various active and reactive powers by various slip (within the operational range) as long as the mechanical torque is equal to the electrical torque. When DFMG is connected to the turbine, the electrical active power of DFMG is defined by the power/speed characteristic of a turbine.

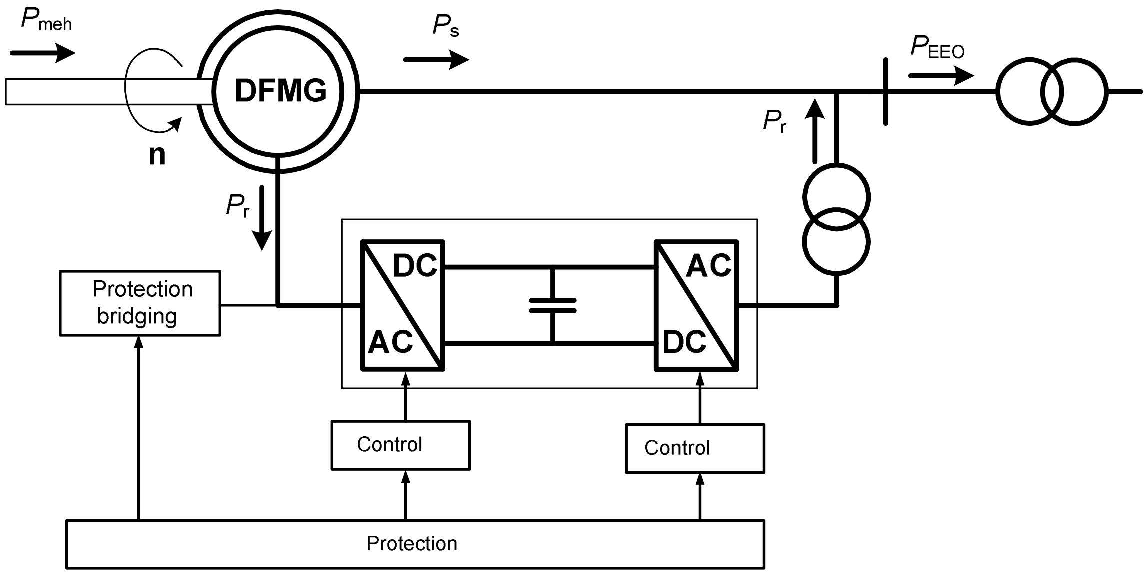


Fig. 1: A basic scheme of a DFMG

According to (1) and according to Fig. 1 we can schematically show the dependence of the power-flow from the mechanical power. Power-flows within DFMG are presented in Fig. 2. Losses of converter and transformer are neglected.

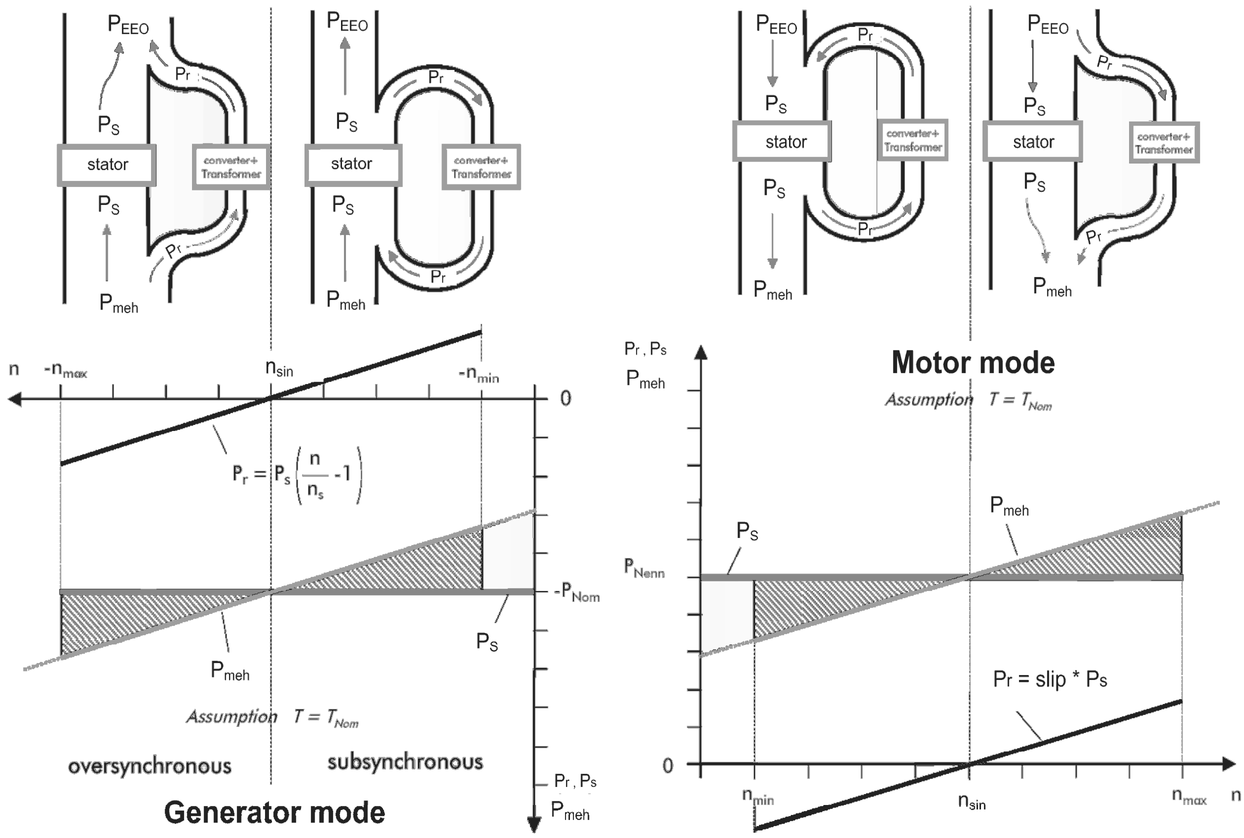


Fig. 2: Power-flows within a DFMG

The meaning of symbols in Fig. 2 is following:

P_r - active power flow through the rotor and converter,
P_{meh} - mechanical power on the shaft,
P_s - active power that flows from the stator to the grid,
P_{EEO} - total active power from the DFMG to the grid,
n - speed,
n_{sin} - synchronous speed.

Proper control of frequency converter is essential part of DFMG. Basic principle of control of AC/DC converter is decoupling of electro-mechanical torque and excitation on the rotor-side of converter and decoupling of active and reactive power control on the network-side of converter.

In this way it is possible to control active and reactive power of the stator (when the speed is defined) or speed and reactive power of the stator (when the active power of the stator is defined) plus active and reactive power of the rotor. It should be mentioned that the protection of converter is carried out with bridging of rotor circuit using the ohmic resistance and semiconductor switch. In the literature this protection function is denoted as "crow-bar" control.

The converter is controlled in such a way that the regulation of electro-mechanical torque and excitation on the rotor-side of converter are decoupled. The active and the reactive power on the network-side of converter are also decoupled [1] - [4].

Various other protection functions are included in the control of the converter, but it is beyond the scope of this paper. More details about the control of a DFMG can be found in [5]-[10].

2.1 Voltages and currents of DFMG

The amplitude of rotor voltage is proportional to the rotor speed. The frequency of the voltage on the rotor f_r is equal to the slip—the same is valid for asynchronous machines—and is defined with the frequency of the stator as:

$$f_{\mathrm{r}} = f_{\mathrm{s}} \cdot s \quad (2)$$

When slip changes, for constant torque (i.e., for constant rotor current) the amplitude of the rotor voltage changes because of changing rotor impedance, which is proportional to the frequency of the rotor current:

$$X_r = 2\pi f_r \cdot L_r \quad (3)$$

where X_r stands for rotor reactance, f_r stands for frequency of rotor current and L_r stands for rotor inductance.

Voltages and currents on the stator and on the rotor at -2% slip are shown in Fig. 3.

Voltages and currents by greater slip (-5%) are shown in Fig. 4. In Fig. 3 and 4 black colors is used to show stator values while green colour is used for rotor values. By the greater slip a larger frequency and amplitude of rotor voltage is applied, while the amplitude of the rotor current (and consequently the torque) remains unchanged.

Considering asynchronous machine, proper rotor current is automatically set according to the mechanical torque as the consequence of induced rotor voltage, the amplitude of which is proportional to the frequency on the rotor. This means that together with the increasing of the slip the frequency and the magnitude of rotor voltage increase and consequently rotor current, which defines the torque, increases.

Considering DFMG, relations are the same, only that the frequency and the amplitude of rotor voltage and rotor current (and consequently the speed and torque) are controlled using a converter

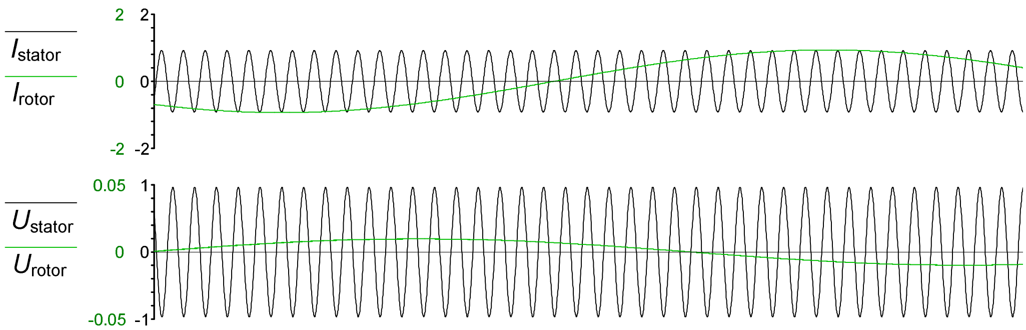


Fig.3: Currents and voltages of the stator and the rotor by -2% slip

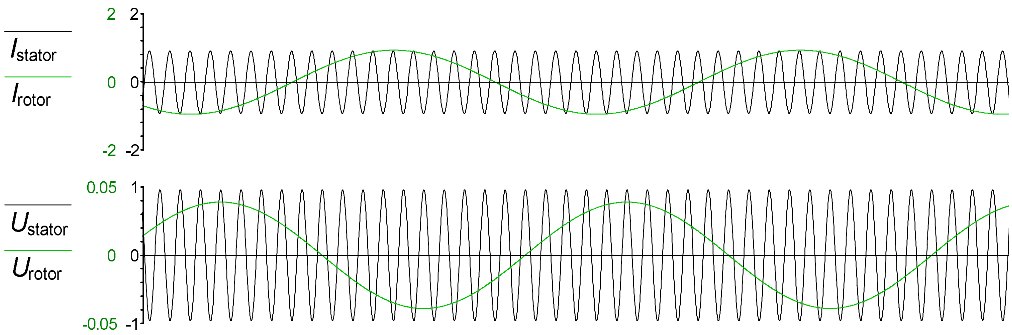


Fig.4: Currents and voltages of the stator and the rotor by -5% slip

3. THE DYNAMIC BEHAVIOR DURING THE FAULT

During the fault and shortly after the fault clearance a crow-bar protection disconnects the converter from the rotor and short-circuits rotor windings. In this way a DFMG behaves as an asynchronous machine. Because of high fault currents DFMG's rotor reactances saturate. After fault clearing, reactances do not de-saturate immediately and consequently the current trough the rotor—and consequently an electrical torque—is much greater than it would be according to the "static" power-slip characteristic (i.e., characteristic in steady-state after the de-saturation of machine's reactances). On the other side, voltage magnitude of the network after a fault clearance is lower then it was before the fault and consequently an electrical torque is decreased. The dependence of active power P on the network voltage magnitude U_{net} and rotor reactance X_{rot} can be assigned as

$$P \approx P_s \cdot \frac{U_{net}^2}{X_{rot}} \tag{4}$$

where P_s stands for a constant that depends on slip and structure of a DFMG, U_{net} is a network voltage magnitude and X_{rot} is a rotor reactance. After the fault clearance the active power P changes according to the trajectory of U_{net}, X_{rot} and slip. The resistance of rotor windings plus resistance of a crow-bar protection affect the transient. The effects of various resistances of crow-bar protection are presented in following sub-chapters.

3.1 Static power-slip characteristic

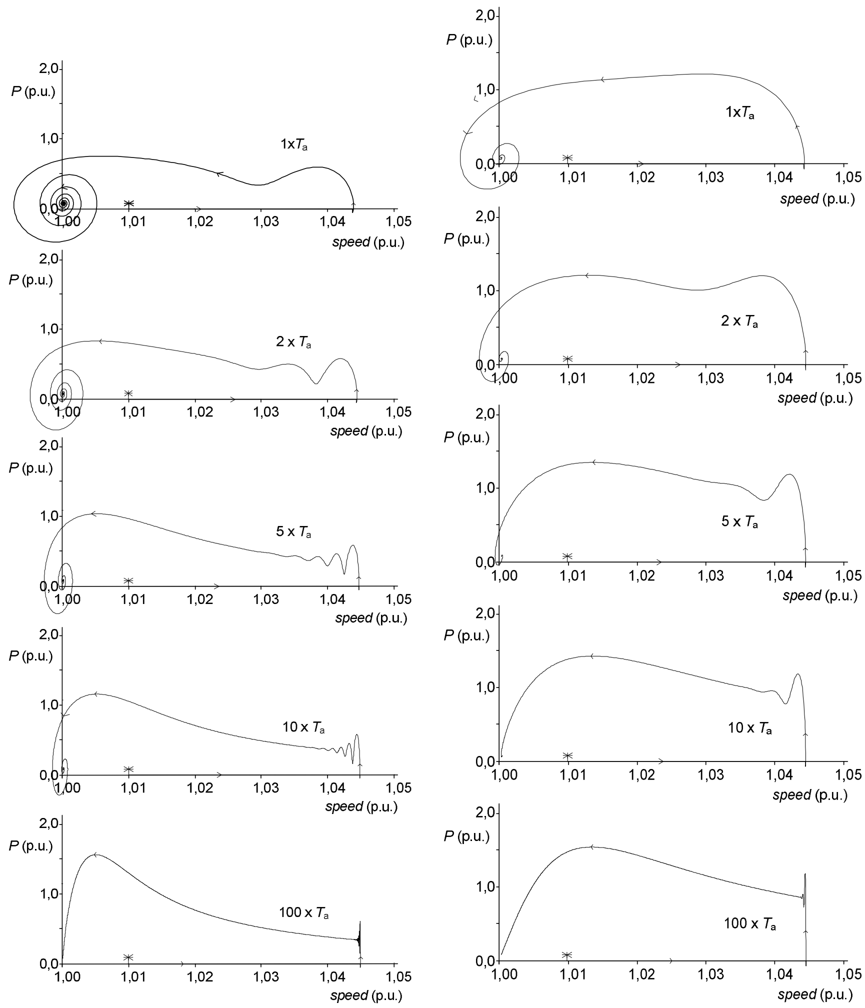
In the first stage we try to obtain a "static" power-slip characteristics characteristic, i.e., characteristic in steady-state after the de-saturation of machine's reactances. In order to obtain these characteristics, in the model of DFMG we can enlarge the mechanical part of electro-mechanical oscillation, i.e., we can enlarge the machine's starting time constant T_a and the duration of the fault. In this way the electrical part (i.e., saturation of reactances) of electro-mechanical oscillation decreases faster relative to the mechanical trajectory (i.e., trajectory of rotor speeds). After de-saturation the trajectory follows the "static" power-slip characteristic and in this way we can determine this characteristic. After the fault clearance a crow-bar protection is not deactivated (although in reality a crow-bar protection is deactivated after a defined time period after the fault is cleared). It should be noted that the effect of the reduced network voltage magnitude is still present.

Fig. 5a and 5b present trajectories of rotor speed after the fault for various values of starting time constants T_a as multiple values of its real value. In Fig. 5a the resistance of crow-bar is set to 0 p.u. (i.e. rotor windings are short-circuited) while in Fig. 5b this resistance is set to 0.0034 p.u. (i.e., double resistance of rotor winding). The last trajectories in both figures goes mainly on the static power-slip characteristic because reactances are de-saturated before rotor speed starts to decrease and in this way static power-slip characteristic can be determined. In the same way this characteristic was determined for greater resistance of crow-bar protection (0.017 p.u., i.e., ten times greater than the resistance of the rotor winding).

The active power before the fault is relatively low—about 0.08 p.u.—in order to enable long duration of the fault and consequently high rotor speed at the end of the fault. Besides a stable point of operation before and after the fault is near synchronous speed and in this way power-slip characteristic can be obtained also in the area of the synchronous speed.

3.2 The effect of the resistance of crow-bar protection

In the second stage we try to obtain how the resistance of crow-bar protection affect the power-slip trajectory. Figures from Fig. 6a to 6c present trajectories of DFMG with activated crow-bar protection—in this case DFMG operates as an asynchronous machine—during and after the fault for various values of crow-bar resistance and various clearing time t_{off}. After the fault-clearance a crow-bar protection is not deactivated in order to show the effect of saturation and voltage reduction, although in reality a crow-bar protection is deactivated after a certain time period after the fault clearance. Simulations were performed in a single-machine infinite-bus test system. Resistance of crow-bar protection is set to 0 p.u. (i.e. rotor windings are short-circuited), to 0.0034 p.u. (i.e., double resistance of the rotor winding) and to 0.017 p.u. (i.e., ten times greater than the resistance of the rotor winding), respectively. The active power before the fault is set to 1.0 p.u.. The last trajectory in each figure presents an unstable case.



a) b)

Fig.5: a) Trajectories of rotor speed for various values of T_{a} at resistance of crow-bar protection set to 0 (i.e. rotor windings are short-circuited)
b) Trajectories of rotor speed for various values of T_{a} at resistance of crow-bar protection set to 0.0034 p.u. (i.e., double resistance of rotor winding).

As it can be seen from results, with the increased resistance of crow-bar protection the damping of rotor current increases while an initial active power after the fault clearance as a consequence of the saturation of rotor reactances is decreased. However, greater resistance of crow-bar protection causes power-slip characteristics to be more adequate as it is wider (i.e., rotor speed after the fault that lasts for a few hundred milliseconds is in the area of the peak active power). Consequently, larger critical clearing times can be achieved with greater resistances of crow-bar protection.

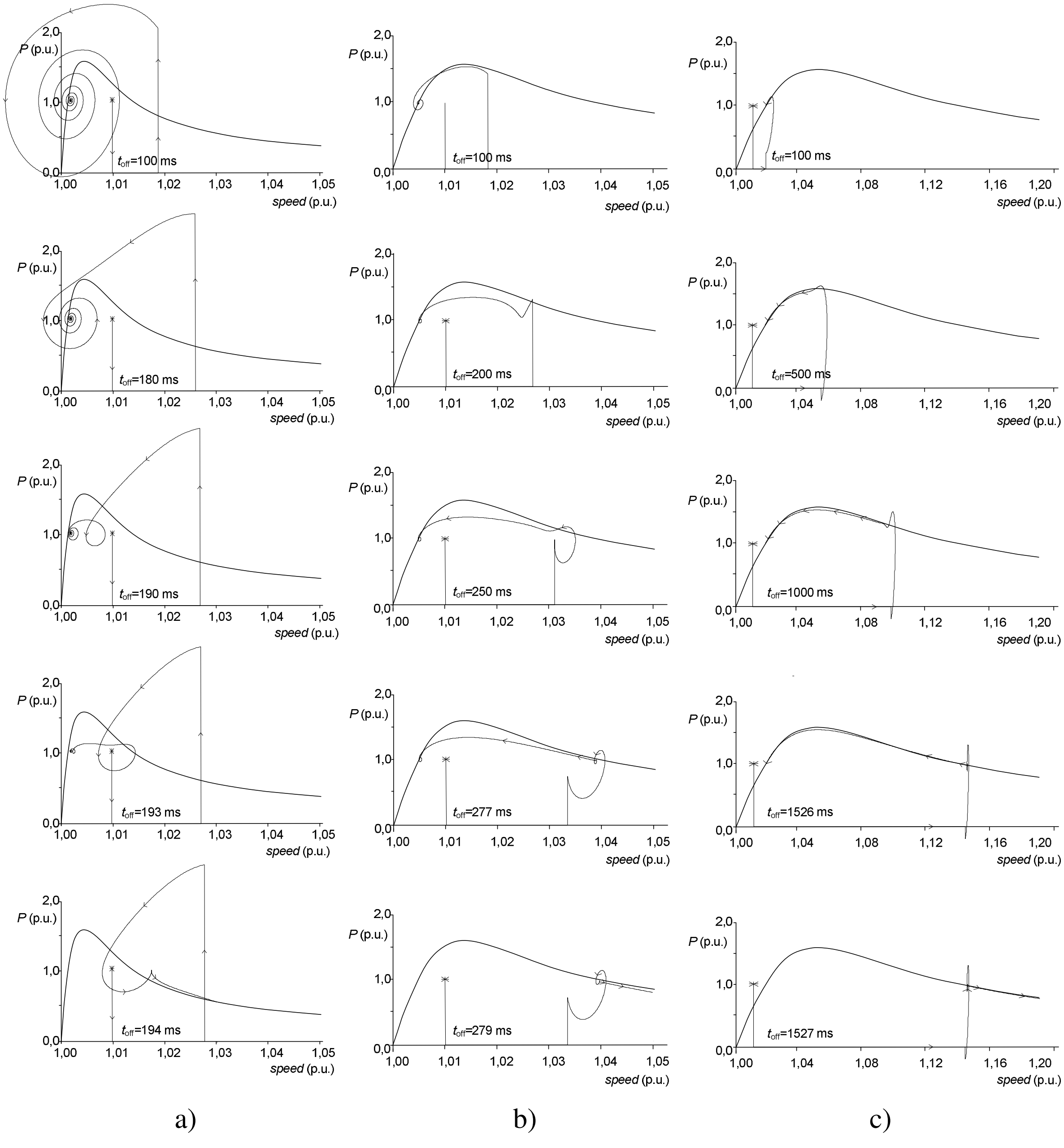


Fig.6: Trajectories of rotor speed: a) $R_{\text{crow-bar}} = 0$ p.u.
b) $R_{\text{crow-bar}} = 0.0034$ p.u.
c) $R_{\text{crow-bar}} = 0.017$ p.u.

4. CONCLUSIONS

During the fault DFMG's crow-bar protection is activated and it disconnects rotor windings from the converter. In this case rotor windings can be short-circuited directly or with the application of ohmic resistances. Consequently DFMG operates as an asynchronous machine. In the case of a low resistance of crow-bar protection electro-magnetic transients appears as a consequence of saturation of DFMG's reactances.

Results of analyses of DFMG behavior show that in the case of low resistance of crow-bar protection electro-magnetic transients during and after the fault affect the torque of a DFMG in such an extent that consideration of "static" power-slip characteristic that is valid for steady state (after the de-saturation of machine's reactances) is not acceptable. Greater resistances damp these oscillations and on the other hand cause power-slip characteristics to be higher in the area of higher speeds. In this way larger critical clearing times can be achieved.

To obtain an optimal resistance of crow-bar protection (in order to augment the transient stability), DFMG should be considered in the model of the real network in order to consider actual voltage reductions and to consider interactions between multiple machines. However, this is the topic of our future work.

5. LITERATURE

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AUTHOR'S ADDRESS

doc.dr. Valentin Ažbe
prof.dr. Rafael Mihalič

University of Ljubljana, Faculty of electrical engineering,
Tržaška 25, 1000 Ljubljana, Slovenia

Tel: + 386 1 4768 415 Fax: + 386 1 4768 289
e-mail: valentin.azbe@fe.uni-lj.si