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SIMULATIONS OF VOLTAGE SAGS IN AN INDUSTRIAL INSTALLATION FEATURING A LARGE INDUCTION MOTOR

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Abstract: This paper addresses the problem of voltage sags during various modes of operation of the directly connected 6 kV squirrel cage induction motor. Simulink model was employed in order to investigate the system dynamic performance and countermeasures against voltage sags upon motor start, rapid load change and steady state operation. Paper presents the comprehensive approach to the analysis of such phenomena using various computer tools. A simple method to extract detailed data of the squirrel cage induction motor using INDSYNW (EMTP-ATP subroutine) is presented herein. Simulink results were additionally verified using NEPLAN.

Key words: STATCOM, reactive power, induction motor.

1. INTRODUCTION

Induction motors are widely used in various applications [4]. Such popularity is to be owed to their controllability, reliability and broad range of powers [14]. Still, there are certain drawbacks that often need a special treatment during system design or upgrade. High starting current and low power factor (PF) are often addressed as most important issues [4, 14, 15]. The above features may become problematic due to both internal requirements regarding the system operation (voltage drops, conductor ratings) as well as grid operators regulations (PF correction) [4]. Despite the fact that all of these problems do not apply to nowadays commonly used inverter-fed drive systems, there are still installations where directly connected motors are being operated [11]. In such situation if there is a threat that the equipment will not comply with internal or external requirements, certain steps can be undertaken. One of the methods that may be applied to solve the problem of rapid voltage sags occurring during large induction motor operation is discussed in this paper. The software mentioned in the abstract was chosen as representative from the wide range of similar programs available on the market, that could be applied for this type of calculations (i.e. DigSilent PowerFactory, PSCAD, EMTP-RV).

The research question of this paper is as follows: "Is it possible to apply the proposed software for efficient and reliable simulation and analysis (both dynamically and in the static way) of the response of the power system during direct start and overload of an induction motor? When only the basic data of motor are available".

2. BACKGROUND AND MODELING

2.1. Reactive power management in power systems

Reactive power management is one of the most crucial elements of power system operation (both globally and locally). The problems that are related to the reactive power management are for example: voltage change, rapid voltage sags and swells, flicker or PF correction [2, 4]. All of the abovementioned voltage related phenomena can adversely affect the operation of the electrical equipment (deep investigation of this influence is not carried out herein) whereas PF correction is usually applied in order to meet Transmission System Operator's requirements, decrease conduction losses and prevent transmission system overload [4].

The employment of some sort of reactive power compensation system may be a remedy to the phenomena listed above. In this case fixed or switched capacitor bank, fixed or tunable reactors, SVC or STATCOM may be applied [4], [5]. One has to bear in mind that only the solution incorporating a smooth and continuous reactive power control will provide voltage stability upon the motor start or during load variations.

In order to obtain ratings of the compensator a few methods of establishing the demand for reactive power can be applied. Those are: measurements, analytical calculations or simulations. The advantage of the last method is that it allows to get a fairly accurate estimation - similarly to calculations by hand – however it also enables to analyse the dynamic states.

The nature of voltage variation caused by the load was comprehensively described (also by means of phasors) in [3]. It should be noted that this paper focuses only on the voltage regulation mode. The PF correction is not addressed herein. The topic of the induction motor starting and related phenomena was discussed e.g. in: [16, 17, 18, 19].

2.2. STATCOM description and control

This paper focuses on the performance of Static Synchronous Compensator (STATCOM) which is a flexible solution that can be applied in power generation, transmission and distribution [2, 4, 5]. STATCOM is a voltage source inverter based device with capacitor connected at the DC link [5]. It is installed in shunt at desired system location. STATCOM can provide both capacitive or inductive reactive power to the system [4, 5]. For this study a simplified model of STATCOM was adopted. It comprises simple control system and controlled current sources. This means that the switching of semiconductor valves was not considered [4]. The principle of operation of the control system consist in voltage regulating loop featuring PI controller (Figure 1). The main objective of the control is to maintain the voltage magnitude (calculated based on Clarke transformation [12] - Equations 1 and 4) at its rated value (1 p.u.). The control is applied on synchronous rotating reference frame (*dq0*) where the set point for the quadrature component is delivered by the PI [5]. The direct component (that reflects active power) is set to zero. The coordinate's transformations (Equations 2 and 3 [13]) require a proper grid synchronization. This function is realized by means of Phase-Locked Loop (PLL) algorithm presented in Figure 2 [10]. The gains of the voltage loop PI controller are as follows: $K_p = 1$, $T_i = 0.00064$ whereas the same parameters in case of PLL account for $K_p = 500$, $T_i = 0.0001$. The gains were found iteratively to ensure good dynamics and errors elimination.

$$\begin{cases} V_\alpha = V_a \\ V_\beta = \dfrac{V_a + 2V_b}{\sqrt{3}} \end{cases} \quad (1)$$

$$\begin{cases} V_d = V_\alpha \cos\theta + V_\beta \sin\theta \\ V_q = -V_\alpha \sin\theta + V_\beta \cos\theta \end{cases} \quad (2)$$

$$\begin{cases} V_a = V_q \cos(\theta) + V_d \cos(\theta) \\ V_b = \dfrac{-\cos(\theta) + \sqrt{3}\sin(\theta)}{2} V_q + \dfrac{-\sin(\theta) - \sqrt{3}\cos(\theta)}{2} V_d \\ V_c = -(V_a + V_b) \end{cases} \quad (3)$$

$$V_{mag} = \sqrt{V_\alpha^2 + V_\beta^2} \quad (4)$$

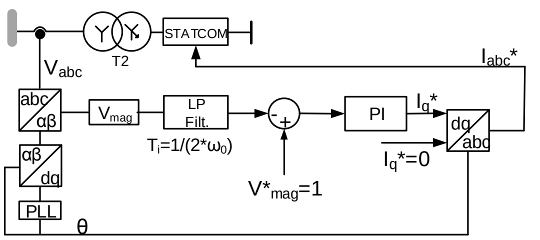

Fig. 1. Control structure used for STATCOM voltage regulation

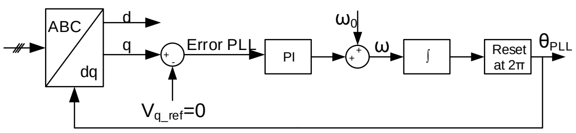

Fig. 2. Phase-Locked Loop

2.3. Squirrel induction motor model

Squirrel cage induction motor model was built based on approach presented in [1]. The machine was modelled in Simulink as a fifth order model that operates in SI units. Blocks from the default Simulink library were used to prepare the model. The interface to electrical circuit built using SimPowerSystems was done by means of controlled current sources. Due to discrete domain implementation a parasitic shunt resistance of 1 kΩ was applied for numerical stability [9]. The equivalent circuit parameters of the motor such as resistances and reactances (Table 2) were estimated based on its rating plate parameters (Table 1) using auxiliary EMTP-ATP application INDSYNW (method based on [8]). Unfortunately the limited accuracy of INDSYNW imposed the necessity of parameters correction. The steady state test in Simulink was conducted in order to verify the model (Figure 3). During the test power consumed by the motor was verified. In order to get the proper *cosφ* the mutual inductance had to be modified accordingly. Implementation of the motor model in NEPLAN requires only the basic parameters from Table 1, hence no parameters adjustment is necessary. Despite its constrained precision, INDSYN provides good estimates of the parameters that are usually troublesome to obtain.

In the case studies 1 and 2 each motor was assumed to be burdened with a fan type of load and fixed load for case studies 3 and 4. The NEPLAN load flow module calculations do not allow to analyse voltage sags upon motor start. Therefore in this case only a steady state was considered.

Table 1. Parameters from rating plates of the motors

Parameter	Motor 1	Motor 2
Moment of inertia, *J* [kg.m^2]	20.7	59
Number of poles, *n* [-]	4	4
Rated voltage, V_n [kV]	6	6
Rated frequency, f_n [Hz]	50	50
Rated power, P_n [MW]	1	2
Power factor, *cosφ*	0.857	0.887

Table 2. Detailed data of the motors

Parameter	Motor 1 (INDSYN)	Motor 1 (corrected)	Motor 2 (INDSYN)	Motor 2 (corrected)
X_m [Ω]	106.786	**66.207**	66.585	**39.95**
X_{ls} [Ω]	2.233	2.233	1.061	1.061
X_{lr} [Ω]	2.233	2.233	1.061	1.061
R_s [Ω]	0.285	0.285	0.147	0.147
R_r [Ω]	1.1648	1.1648	0.312	0.312

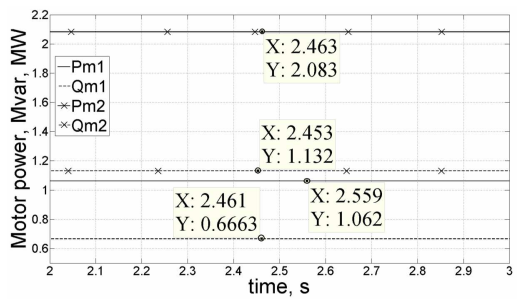

Fig. 3. Active and reactive power consumed by M1 and M2 at rated load P_{M1}= 1.062 MW, Q_{M1} = 0.6663 Mvar, $cos\varphi_{M1}=0.847$; P_{M2} = 2.083 MW, Q_{M2} = 1.132 Mvar, $cos\varphi_{M2}$ = 0.879

2.4. Passive elements of the system

Elements such as system equivalent, transformers and cables that are visible in Figure 4, were modelled using elements from SimPowerSystems and NEPLAN default libraries. The data of the transformers are presented in Table 3 whereas cable parameters are gathered in Table 4. The short circuit power at 35 kV side is represented by the equivalent voltage source in series with RL elements that reflect following assumed data: $S_k'' = 100$ MVA and $X/R = 14.25$.

Table 3. Data of power transformers T1 and T2 (based on [7])

Parameter	T1	T2
Vector group	YNd11	Yyn
Rated power	20 MVA	11 MVA
Voltage ratio	35 kV / 6 kV	6 kV/0.4 kV
Copper losses	140 kW	65 kW
No-load losses	18 kW	6 kW
Impedance	10 %	7 %
L_{HV}, L_{LV}	16.84 mH, 0.286 mH	0.363 mH, 1.6 uH
R_{HV}, R_{LV}	0.371 Ω, 0.0063 Ω	0.01 Ω, 0.000044 Ω

Table 4. Data of cables C1 and C2 [6]

Parameter	C1	C2
Type	3x1x 50 mm^2	3x1x 120 mm^2
Length	300 m	150 m
Resistance	0.387 Ω/km	0.153 Ω/km
Inductance	0.4 mH/km	0.34 mH/km
Capacitance	0.3 uF/km	0.42 uF/km

3. SYSTEM DESCRIPTION AND CASE STUDIES

The overall diagram of the system under study is presented in Figure 4.

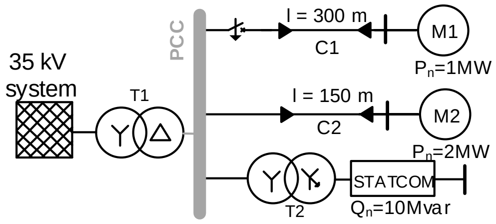

Fig. 4. Overall system diagram

The list of case studies is presented in Table 5. As can be noticed both motors are in scope of transient analysis. However M2 is assumed to have a soft starter, therefore its inrush current is not a concern. This argument is essential to establish the proper ratings of the reactive power compensating device.

Table 5. List of investigated case studies

Case no.	Status of the equipment		
	Motor 1	Motor 2	STATCOM
1	t_{on}=0.7 s	t_{on}=0 s	t_{on}= ∞
2	t_{on}=0.7 s	t_{on}=0 s	t_{on}= 0 s
3	t_{on}=0 s	$t_{overload}$=0.7 s	t_{on}= ∞
4	t_{on}=0 s	$t_{overload}$=0.7 s	t_{on}= 0 s

Both scenarios M1 start (cases 1 and 2) and M2 50% overload (cases 3 and 4) are analysed in Simulink where the steady state can be also observed. Nonetheless due to software limitations only the steady state is analysed using NEPLAN.

4. SIMULATION RESULTS

The results of NEPLAN calculations are depicted in Figure 5. They are presented in a graphical form that indicates the power flow in branches and voltage level at the point of common coupling (PCC).

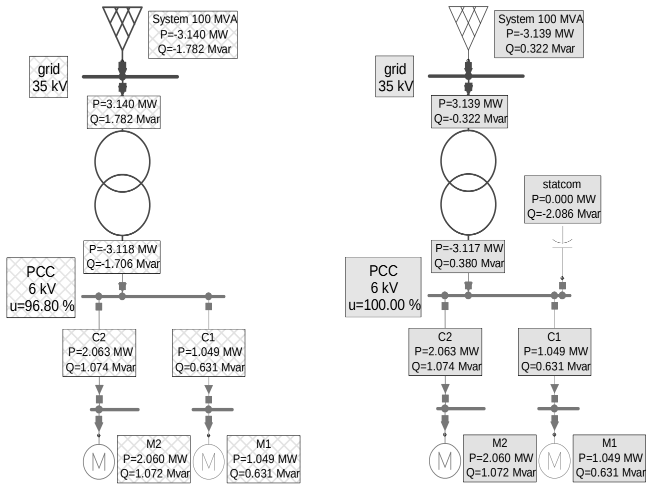

Fig. 5. NEPLAN steady state calculations with both motors at rated load (left - no STATCOM, right with STATCOM)

The results of dynamic simulation in Simulink (all presented starting from t = 0.6 s when the steady state occurred) are presented below (Figure 6 – Figure 11). Instantaneous voltage (only cases 1 and 2) at the PCC and power delivered by the STATCOM is depicted for cases listed in Table 5. To get a better visibility for cases 3 and 4, zoomed voltage magnitude was presented. Data tips are used for easy result comparison.

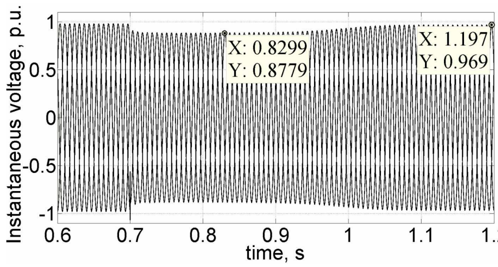

Fig. 6. Instantaneous voltage at the PCC for case study 1

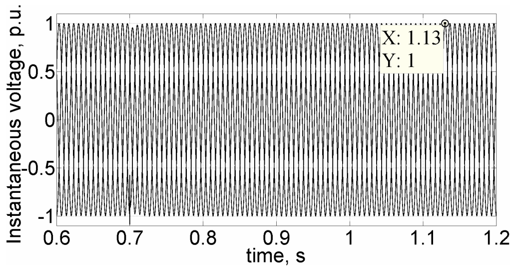

Fig. 7. Instantaneous voltage at the PCC for case study 2

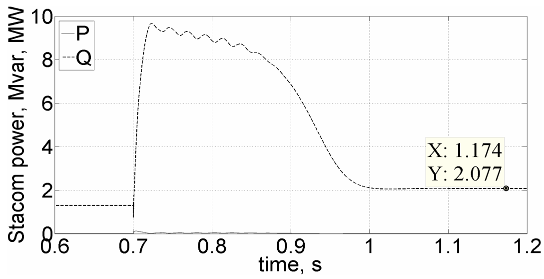

Fig. 8. Power delivered by the STATCOM for case study 2

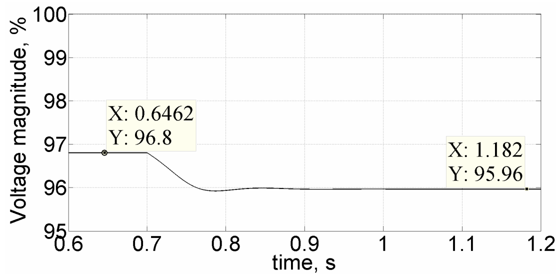

Fig. 9. Voltage magnitude at the PCC for case study 3

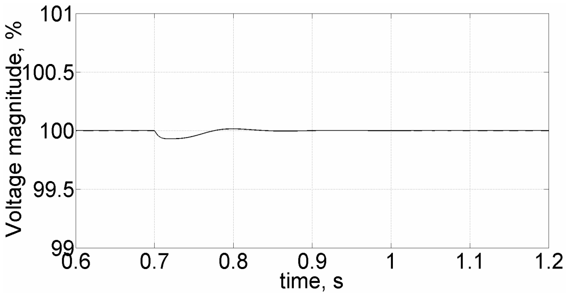

Fig. 10. Voltage magnitude at the PCC for case study 4

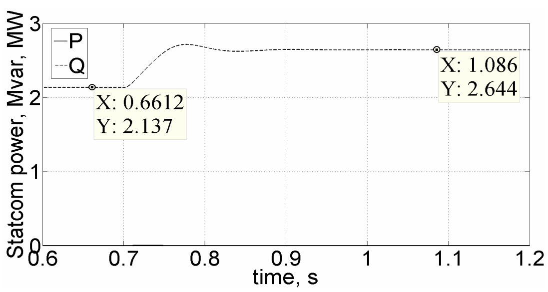

Fig. 11. Power delivered by the STATCOM for case study 4

5. OBSERVATIONS AND CONCLUSIONS

The comprehensive approach to establishing the required level of reactive power compensation was presented herein. Three software environments namely INDSYNW, Matlab/Simulink and NEPLAN were used to prepare the model of exemplary network and calculate voltage sags during transient and steady state. The outcome of the analysis are the power required to compensate for the voltage depression, duration of starting process and the evaluation of dynamic response of the compensating device. Slight voltage oscillations were recorded upon the breaker making operation (0.7 s) in cases 1 and 2. It is caused by presence of long cable and the fact that it is being charged. It was clearly demonstrated that by using proposed software it is possible to deliver high quality estimates (useful in the engineering design process) without detailed motor data that are usually hard to obtain.

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SYMULACJA ZAPADÓW NAPIĘCIA W UKŁADZIE Z SILNIKAMI INDUKCYJNYMI O DUŻYCH MOCACH

Słowa kluczowe: moc bierna, rozruch, silnik indukcyjny klatkowy.

Artykuł prezentuje analizę zapadów napięć w sieciach SN podczas pracy silnika indukcyjnego klatkowego dużej mocy przy użyciu wybranych programów. Dzięki zastosowaniu aplikacji INDSYNW służącej do oszacowania szczegółowych danych silników, możliwe jest wykonanie analiz nie tylko podczas stanu ustalonego, lecz także w czasie rozruchu lub przeciążenia maszyny. Analizę przeprowadzono w programach NEPLAN oraz Simulink.