Journal of Power Technologies 103 (4) (2023) 218 -- 229

Dynamic performance improvement of small-scale synchronous generator adjacent to electric arc furnace load

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Abstract

Electric arc furnace has a variable power consumption with time that causes mechanical oscillations in the adjacent small scale synchronous generators, and consequently, decreases their life. In this paper, we first provide a model for electric arc furnace and validate it using actual measured data. In this paper a real distribution system consisting of the small-scale synchronous generator, which feeds industrial loads, including electric arc furnaces, is analyzed and evaluated based on the simulation of the time domain. Using analytical studies and simulation results, the appropriate value for controller parameters of the prime mover is determined in such a way that the mechanical oscillations of the small-scale synchronous generator created by the electric arc furnace are reduced. In addition, the response of the transient mode of the small-scale synchronous generator is also considered in the proper setting of the parameters. Finally, reliability and effectiveness of the proposed parameters are evaluated using real measurement data

Keywords: electric arc furnace, small-scale synchronous generator, generator torque, microgrid control

Introduction

One of the most important ways to produce steel on a large scale is to use electric arc furnaces. Electric arc furnace due to creation of harmonics lower and higher than the rated frequency, may affect the equipment of power system and even other consumers. One of the most significant effects of furnace on the network can be voltage fluctuations [1], transient over voltages [2], reduction of power quality [3], power oscillations [4,5] and torsional oscillations in synchronous generators [5,6].

Solutions are also presented in numerous articles. Using static var compensators [7], static synchronous compensator (STATCOM) [8], active series reactors (ASR) [9] and energy storage is one of the most important methods. Also, a fly wheeling is used as a mechanical filter to reduce torsional fluctuations introduced into the shaft of the generator [6].

Power outage of these furnaces for a long time causes solidification of the melting material inside arc furnace. Hence, maintaining high reliability in the supply of arc furnaces electricity is necessary. On the other hand, the high cost of supplying electricity, along with the existing economic incentives, caused some industries to use small scale synchronous generators (SCSG) along with electricity supply from the power grid [10]. In this case since electric arc furnace consumes variable power, it may have many effects on small scale synchronous generators such as fluctuation in electric power and mechanical torque and changing speed of the generator rotor. This intermittent stress causes SCSG lifetime to be considerably reduced [6]. These fluctuations also generate torsional torque in synchronous generator axis [4-6,11].

In [5], a factory includes electric arc furnace fed by SG. SG is modeled by mass and spring and torsional oscillations on the turbogenerator axis due to voltage fluctuations of arc furnace load being investigated. It is shown that power oscillation due to electric arc furnace causes the sub synchronous component in synchronous generator torque. In [6], a 90-ton steel plant uses small scale SGs and is modeled like [5]. However, in this paper a mechanical low pass filter is proposed to improve the fluctuations and tensions of sub synchronous oscillation. More losses in addition to the high costs are the result of this proposal.

In [11], considering the electric arc furnace model as a pulsing load model and synchronous generator as a mass and spring model, the effect of electric arc furnace on mechanical torque of synchronous generator has been studied. In the reference, it has been stated that the greatest effect of the furnace on the torque of the synchronous generator is during the melting process and hence the effect of the furnace only has been studied during this time.

In this paper, to analyze the effect of electric arc furnace on small scale synchronous generator, a part of the grid connected to the distribution network includes a synchronous generator and electric arc furnace load is considered. EAF model is verified by actual measured data.

To control the prime mover (diesel engine) a traditional PI controller is used. The simulation results show that the proper settings for the diesel engine controller make the number of mechanical oscillations decrease significantly. This method is very easy to use in new small scale synchronous generators with digital controls. The control criteria include reducing mechanical fluctuations in presence of EAF, improving dynamic response of the system during its operation and transient stability. Also, a low pass filter can be added to the PI controller of prime mover to reduce mechanical fluctuations more effectively. In the following, the variable frequency load model for the EAF and its effect on the synchronous generator is studied.

Modeling of system components

The network studied in this paper is shown in Fig. 1. This network can be a part of the Steel Industrial Factory under study. The total power of electric arc is 38 MW. In the case of a synchronous generator connected to the network, this power is divided between the network and the generator. The small-scale generator is an 11 KV generator with a nominal power of 10.8 MW.

Electric arc furnace model

The operation of conventional electric arc furnaces is as follows. First, these furnaces are filled with scrap or sponge iron and then due to the heat generated by the arc, the material inside the furnace is smelted. In the early stages of melting due to inhomogeneity of the material inside the furnace, electric arc length changes in the cathode are intense, resulting in high volatility in power consumption. The environment is relatively homogeneous, resulting in changes in arc length. Electricity is getting lower. In this situation, the fluctuations of the power consumption of the furnace are also less volatile.

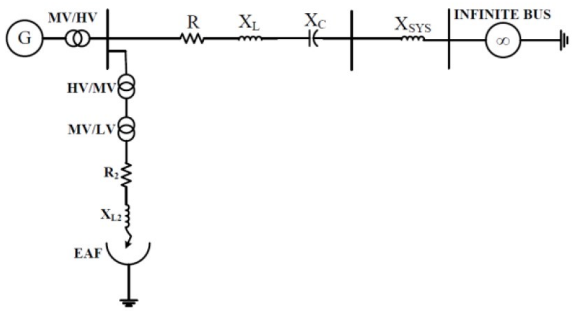

Figure 1: The network includes electric arc furnace and small-scale synchronous generator

Based on the study a static or dynamic model can be used [1]. Since in this paper, we investigate the effects of power oscillation on the torque magnitude of the small generator and low frequency furnace behavior is important, the electric arc furnace is dynamically modeled. The dynamic arc resistance of EAF during the melting stage is calculated using sinusoidal modulation as follows [12]:

$$R_{arc}(t) = R_a(t)(1 + \sin(2\pi f_f t)) \tag{1}$$

In the above equation, the parameter f_f is the furnace fluctuation frequency, with the value of 0.5 to 25 hertz in different furnaces [12,13]. Fig. 2(a) shows the real measured waveform of the furnace current, which in addition to the frequency of the power network, is accompanied by an approximately sinusoidal oscillation with the frequency ranging from 3 to 9 hertz. A part of this waveform is shown in Figures 2(b) which show frequency of oscillations for 3Hz. Based on Fig. 2(b) frequency value in (1) is chosen 3Hz which is well matched with the measurement data.

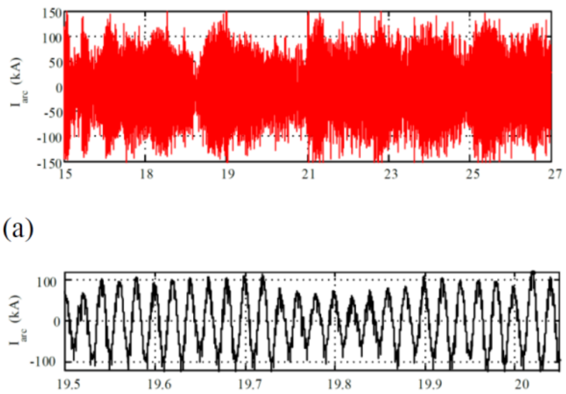

Figure 2: (a)The measured current of the electric arc furnace, (b) part of the signal for 3Hz

Turbin and Generator Model

A small-scale generator is a synchronous generator connected to the primary propulsion of an internal combustion gas engine [14-17]. To control the fuel of this engine when synchronous generator is connected to the network, a PI controller is used to control the true output power of the generator [18-22]. Gas engine model with fuel controller is shown in Fig. 3.

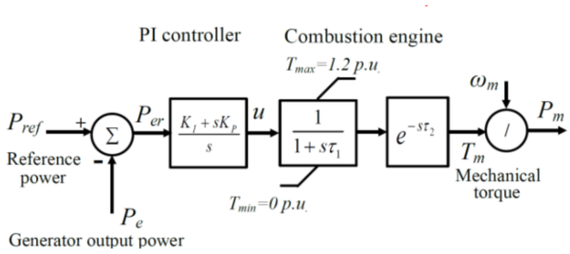

Figure 3: Block diagram of prime mover and fuel controller

For excitation models, the IEEE standard AC5A is used [22]. Also, because the generator is connected to the network, the generator's exciter is set to control reactive power to the network [23].

Torsional oscillations due to power consumption of EAF

Traditionally AVR and governor controller parameters are determined to have a stable network to provide active and reactive power for loads with constant power. Then EAF a variable power load connect to the network is considered. Active output power with parameters of PI controller KP=0.55 and KI=1.0 is shown in Figure 4(a). Mechanical torque also in figure 4(b) indicates that the range of its oscillation is about 0.12 per unit. As seen in Fig. 4(c), fluctuations of mechanical torque change generator speed.

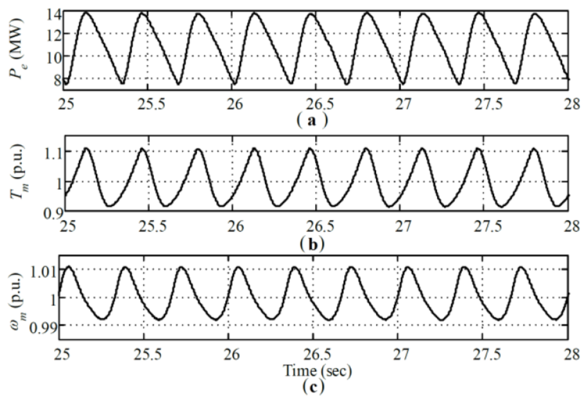

Figure 4: (a) output power of SG, (b) Mechanical torque of turbine, (c) generator speed

Analytical study for parameters effect of prime mover controller on mechanical oscillations

In Fig. (2), block diagram of the prime mover and its simple controller, Taylor expansion is used to linearize the delay block [20] that is:

$$e^{-s\tau_2} \cong \frac{1-0.5s\tau_2}{1+0.5s\tau_2} \qquad (2)$$

To analyze the relation of the mechanical oscillations' magnitude to the control parameters, first transfer function of error power P_{er} and mechanical power is written as follows:

$$\frac{T_m}{P_{er}} = \frac{-K_p\tau_2 s^2 + (2K_p - K_I\tau_2)s + 2K_I}{\tau_2\tau_2 s^3 + (2\tau_1+\tau_2)s^2 + 2s} \qquad (3)$$

Where, P_{er} is equal to the difference between the reference power signal and the generator output power. Error power signal P_{er} changes with frequency f_f due to volatility of the output electric power of the generator. As a result, the error power signal can be written as follows:

$$P_{er}(t) = \sum_{n=1}^{\infty} A_n \sin(2\pi f_f t + \emptyset_n) \qquad (4)$$

Where $A_n, \emptyset_n$ are amplitude and phase of the nth component of Fourier series for $n \times f_f$ frequency. Using the Laplace transform, we have:

$$P_{er}(s) = \sum_{n=1}^{\infty} \frac{2n\pi f_f \cos(\emptyset_n) + \sin(\emptyset_n)s}{s^2 + (2n\pi f_f)^2} e^{-s\tau_2} \qquad (5)$$

By combining eq (3) and (5) the following is obtained:

$$T_m(t) = T_0 + \sum_{n=1}^{\infty} A_n\left[D_n + F_n\cos(2\pi f_f t + \emptyset_n) + G_n\sin(2\pi f_f t) + \emptyset_n)\right] \qquad (6)$$

Where T_0 is steady state mechanical torque. D_n, F_n, G_n coefficients are equal to:

$$D_n = \frac{K_I\cos(\emptyset_n)}{n\omega_f} + \frac{2\tau_2 e^{-\frac{2t}{\tau_2}}(2K_p - K_I\tau_2)}{(2\tau_1-\tau_2)(\tau_2^2 n^2\omega_f^2 + 4)} \times \left[2\sin(\emptyset_n) - n\omega_f\tau_2\cos(\emptyset_n)\right] - \frac{e^{-\frac{t}{\tau_1}}(K_p - K_I\tau_2)(2\tau_1+\tau_2)}{(2\tau_1-\tau_2)(n^2+4)} \times \left[\sin(\emptyset_n) - n\omega_f\tau_1\cos(\emptyset_n)\right] \qquad (7)$$

$$F_n = \frac{1}{n\omega_f(\tau_2^2 n^2\omega_f^2+4)(\tau_1^2 n^2\omega_f^2+1)} \times \begin{bmatrix} K_P\tau_1\tau_2^2 n^4\omega_f^4 \\ -(4K_P\tau_1 + 4K_P\tau_2\tau_2^2 - 4K_I\tau_1\tau_2) \\ \times n^2\omega_f^2 - 4K_I \end{bmatrix} \qquad (8)$$

$$G_n = \frac{1}{-n\omega_f(\tau_2^2 n^2\omega_f^2+4)(\tau_1^2 n^2\omega_f^2+1)} \times \begin{bmatrix} n^3\omega_f^3 \\ \times(K_P\tau_2^2 - K_I\tau_1\tau_2^2 + 4K_P\tau_1\tau_2) \\ +n\omega_f \\ \times(4K_I\tau_1 - 4K_P + 4K_I\tau_2) \end{bmatrix} \qquad (9)$$

Where $\omega_f = 2\pi f_f$.

According to the above description, amplitude of mechanical oscillation is calculated as follows:

$$M_n = \sqrt{A_n^2(F_n^2 + G_n^2)} = \frac{A_n}{2n\pi f_f}\sqrt{\frac{K_I^2 + (K_P \times 2n\pi f_f)^2}{(2n\pi f_f)^2 + 1}} \qquad (10)$$

To reduce mechanical oscillations, the value of M_n should be reduced. As seen from eq (10), it M_n has a direct relation with K_P and K_I increases with increasing them. Then in order to reduce the amplitude of the fluctuations, integral and proportional factors must be reduced in the prime mover controller. As seen in (10) parameter K_P is also multiplied by a large gain, which can be more effective in reducing or increasing M_n than K_I parameter. As a result, the K_I must be selected as small as possible.

Numerical study for parameters effect of prime mover controller on mechanical oscillations

To investigate the effect of controller parameters on the mechanical oscillation numerically, the index GPD is defined as follows:

$$GPD_X = \frac{X_{max} - X_{min}}{X_{av}} \times 100 \quad (11)$$

Where X represents system variables such as output power of generator P_e, output torque if prime mover T_m, or mechanical speed ω_m Maximum, Minimum, and Average values of variable X for normal operation is $X_{\max}, X_{\min}$ and X_{av} respectively. By optimizing this index, the mechanical oscillation rate of the generator or prime mover will be minimized. GPD index for different variables P_e, T_m and ω_m using the network simulation for different values of K_I and K_P are calculated where the frequency of the arc furnace fluctuations is 3 Hz and shown in Fig. 5. It can be shown that the network under study is stable for $0.4 \leq K_I \leq 4$ and $0.1 \leq K_P \leq 0.5$. For example, GPD_{Tm} index is calculated for different values of K_P and K_I and frequency values f_f is also shown in Fig. 6.

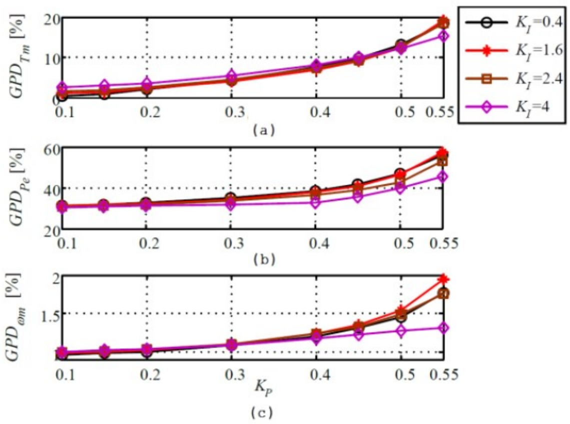

Figure 5: GPD index for (a) mechanical torque (b) reactive output power (c) shaft speed of prime mover for different Ki and Kp

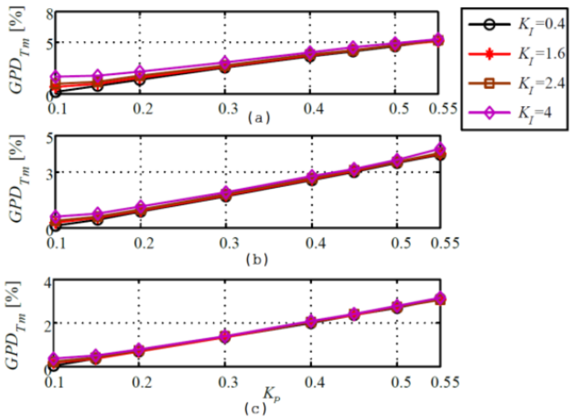

Figure 6: GPD_{Tm} index for (a) f_f = 5Hz (b) f_f = 7Hz (c) f_f = 9Hz for differenr K_i and K_p

According to the simulation results, it is seen that K_p effectively decreases as the value of the GPD_{Tm} parameters drop, while its sensitivity is small with respect to K_I parameters. As a result, to improve mechanical oscillations and increase damp rate, the minimum value must be selected while keeping stability of the system. By comparing figures (5a) and (6) it shows that amplitude of the mechanical oscillations is reduced while increasing the frequency f_f. This result can also be deduced from eq. (10). In the next section of this paper, the effect of prime mover controller parameters on the generator dynamic response is studied.

Synchronous generator dynamic response study

An index for dynamic response

To adjust properly the parameters of the prime mover controller, it is necessary to study their impact on the synchronous generator dynamic response. So, a proper index is needed to ensure that there is a valid dynamic response. In other words, by optimizing this index, proper response from the perspective of settling time, rise time and overshoot will be achieved. Figure 9 shows output power of generator (P_e) for different values of K_I and K_P while (P_{ref}) changes from 0.5 to 1 in per unit. Because of the PI controller, steady state error is equal to zero and therefore, after a while, the output power of the generator is equal to the set point. For different values of the controller parameters, signal P_e with different settling time and frequency of oscillations reach to reference signal P_{ref}. According to the simulation results shown in Fig. 7, the following results are obtained: (1) The parameter K_I has no significant effect on the GPD index, which is an indicator of steady state oscillations, but has a great effect on the dynamic response. (2) The sensitivity of the dynamic response to parameter K_P is less than parameter K_I. (3) The larger values of parameter Ki increase overshot and the small amounts of it will increase the settling time.

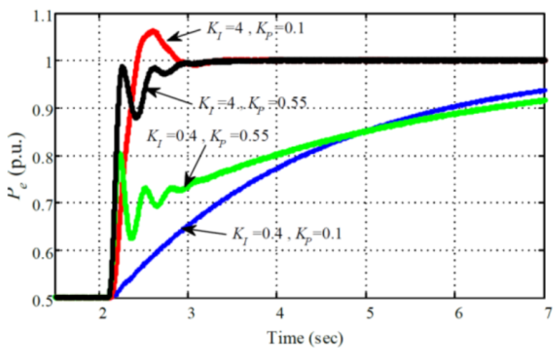

Figure 7: Active output power for different K_i and K_p

To verify the synchronous generator response, index GPI is defined as below:

$$GPI = \int_{t_0}^{\infty} \left[\left(P_{ref} - P_e\right)^2 + K_u u^2 \right] \quad (12)$$

Where t_0 is the time to change power set point. As shown in Fig. 2, output signal U of the PI controller represents the controller's effort to adjust the output power to the desired value. In fact, signal U is input fuel to the prime mover. Parameter Ku is a constant number and is considered to be 0/005 . GPI index is calculated for different values of K_I and K_P and shown in figure (8). According to Fig 8 GPI index, unlike the GPD index, is sensitive to K_I much more than K_P parameter. Therefore, it is necessary to adjust K_P to eliminate the mechanical oscillations and K_I to improve the dynamic response in appropriate values.

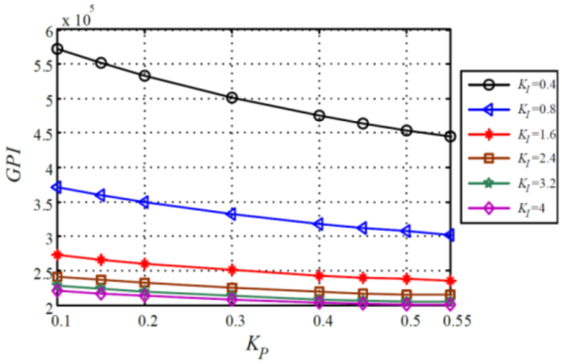

Figure 8: GPI index for different K_i and K_p

An index for transient response

The inertia of the small-scale synchronous generator is low and on the other hand clearing time of a fault in distribution network is long. Therefore, the transient stability of generator is important. The controller system parameters of the generator do not usually change during the fault in the micro-grid and their values affect the transient stability of generator. In this section the effect of controller parameter of K_I and K_p on transient stability of generator is studied. An index CCT was used for this study. CCT index is defined as maximum time for clearing three phase faults without transient instability occurring [24].

During the fault in the network, output power of the generator decreases and, as a result, difference of mechanical power and electrical power (Per in Fig. 2) increases. The positive value of Per in this situation increases the controller output U and therefore increases fuel to the prime mover. As a result, the mechanical torque of the generator increases. Because the generator is not able to transmit this power to the network, the generator speed increases further. Therefore, the longer the trigger controller is slower and the mechanical torque changes slowly during the fault, the increase in the generator speed during the fault will be less. Figure (9) shows the calculated CCT for small scale generator of the study for different values of K_p and K_I parameters. As shown in Figures (9a) and (9b), both the K_I and K_p parameters are effective on the CCT index.

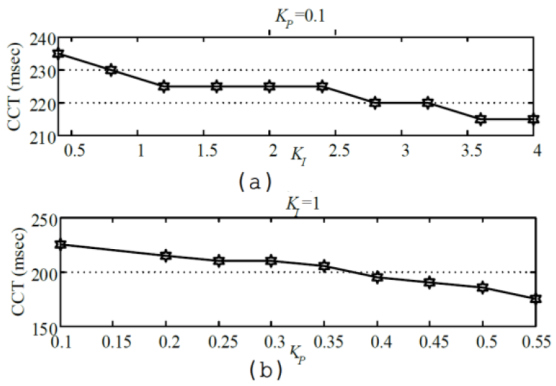

Figure 9: CCT index for different (a) K_i and (b) K_p

However, the effect of the KP parameter is much higher than K_I, because the integrator block does not act instantaneously against the proportional block and needs more time to act. Since the duration of the fault is short and output value of integral block is small during this time, the parameter K_I will have less effect on the CCI index. In addition, to increase the CCT, the parameter K_P must be as high as a small option to be selected. Figure (10a) shows speed of the generator for K_I = 4, and K_P = 0/1, in the case of a three-phase fault that has been cleared after 212 milliseconds. Since the FCT, fault clearing time, is less than CCT in this case (FCT = 212ms), the CCT value as seen in fig 9a is equal to 215 milliseconds, so that the mechanical speed fluctuations are generated, and the post-production generator error can be permanently fixed to the network to stay. However, the shape (-12) indicates that if the FCT value is greater than the coat () FCT = 218ms, the range of fluctuations will increase and not decrease. Therefore, in this case, the generator becomes unstable.

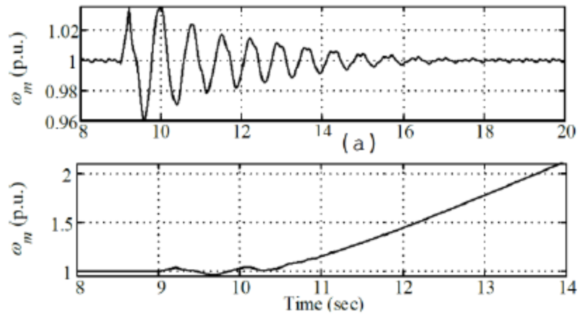

Figure 10: Speed of prime mover for (a) FCT=212ms (b)FCT=218ms

Since the initial stimulus controller parameters had different effects on the introduced indices, in the next section, the appropriate values of these parameters are considered, taking into account all three indicators.

Discussion and review

In this section, according to the sensitivity analysis performed in the previous sections, the optimal parameters of the primary actuator controller are determined to reduce the mechanical stresses on the turbogenerator set and to improve the dynamics of the generator in the face of transient states. In this section, first, the achievements of the preceding sections are summed up and the desired number of the controller parameters are determined. In order to improve mechanical fluctuations, it is recommended to use a low pass filter. At the end of this section, the performance of PI with the network controller under study is evaluated by considering the appropriate parameters proposed in the following two areas:

1. When frequency f_f varies with time.
2. When the actual signal measured as shown in Fig. 3 (a) is used as an electric arc furnace current.

Determining the appropriate values for the controller parameters

In summary, the results of the previous sections can be summarized in three parts:
(1) According to the sensitivity analysis performed in Section (3) and Figures (A) to (5) and (6), selecting a small number for a proportional block reduces the

value of the GPD_{Tm} index; while the K_I parameter does not have much effect on this index. As a result, in order to reduce the GPD_{Tm} value, the K_P parameter should be considered as minimum. Reducing the K_P parameter, in addition to decreasing the GPD_{Tm} value, also reduces GPD_{p_e} and GPDWm indices. In this paper, given the intervals for the stable performance of the network introduced in the static state, the optimal value of the K_P parameter is equal to 0.1 .
(2) According to Fig. 9, the reduction of K_P and K_I parameters improves the CCT index, but the K_I effect is very small. Therefore, it is appropriate that the K_p parameter be considered to be the minimum possible value, which for the network under study in this paper has a minimum K_P of 1.0. The K_I parameter has a negligible effect on the GPD and CCT index, while the value of this parameter has a significant effect on the improvement of GPI index. Therefore, it is appropriate that the K_I parameter be determined based on the GPI index.
(3) According to the sensitivity analysis of Fig. 8, with the proper adjustment of the K_I parameter, a desirable dynamic response can be obtained, and the K_P parameter has a small effect on the value of the GPI index. As the K_I increases, the GPI value improves. Therefore, the K_I must be set to the maximum value, which is 4 in the network under study.

According to the points mentioned, the appropriate values for the K_I and K_P parameters are 4 and $0/1$, respectively. Figure (11) shows the active power output momentum, mechanical torque and productive motor speed in this case.

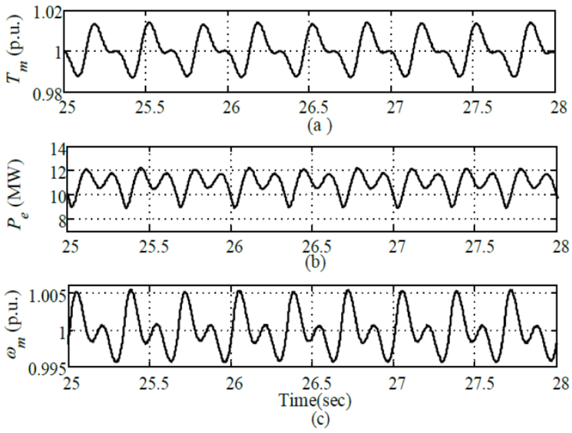

Figure 11: Waveform (a) mechanical torque, (b) momentary output power, (c) productive mechanical speed in optimal mode

As seen in the case of using K_I = 4 and K_P = 0/1, the magnitude of the oscillations of the generator parameters decreased significantly as compared to the initial state examined in Section (3). In this case, the value of the CCT and GPI index has improved compared to the initial state. The CCT increased from 175 to 215 milliseconds, and the GPI dropped from 2.5 to 2.5 × 2.5 to 2.5 × 10.

Since the method used to determine the proper value of the controller parameters is general, it can be used to change the structure of the network. However, the range of controller parameters varies in order to maintain the network, which can be easily calculated using simulation of the network in time simulation software.

Changing the structure of the prime mover controller

Since the input error signal to the PI (P_{er}) controller is calculated on the basis of the output power signal (P_{er}), there will be low-frequency oscillations in the P_{er} signal, resulting in mechanical torque oscillations. Therefore, a suitable way to prevent a governor's response to these fluctuations is to use a low pass filter before the PI controller. Figure (12) shows the block of the primary stimulus and PI controller diagram along with the downstream filter.

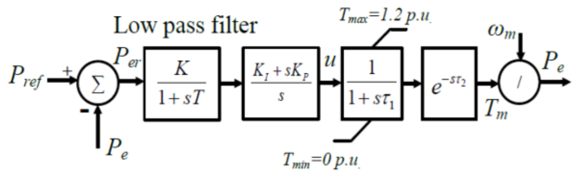

Figure 12: Primary actuator block with PI controller equipped with lowpass filter

The time constant of this filter is determined in such a way that its cutoff frequency is approximately equal to the frequency of the electric arc furnace power fluctuations. The downstream filter used in this article has K = 1 and T = 0.1. Fig. 13 compares the mechanical torque signal (T_m) in the case where the lowpass filter is used, in the absence of this filter. According to this form, the range of mechanical torque fluctuations has dropped by 57%.

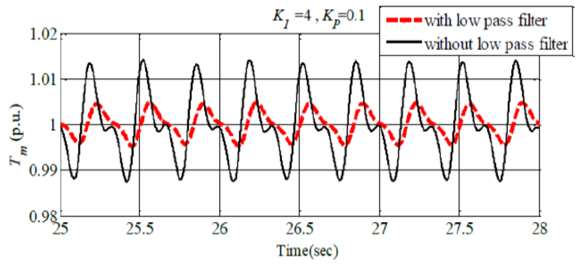

Figure 13: Comparison of mechanical torque in two conditions of use and use of low pass filter

Synchronous generator performance in the case of electric arc furnace with varying frequency fluctuations

All the simulations that have been done so far assume that the parameter f_f is constant and does not change with time. However, during the melting process, the value of the parameter f_f varies with time. Therefore, in this section, productive performance is investigated in the following two scenarios, where the parameter f_f varies.

Modulated signal

In order to model the arc resistance with the frequency of variable oscillations, the parameter f_f in relation (1) is changed per second. Figures (14a) and (14b) show the mechanical torque oscillations of T_m for the initial parameters, K_I = 1, K_P = 55, and the proposed parameters, K_I = 4 and K_P = 0/1 respectively. By comparing this form, it can be seen that by adjusting the optimal parameters, the amount of mechanical torque fluctuations is significantly reduced for various values of f_f.

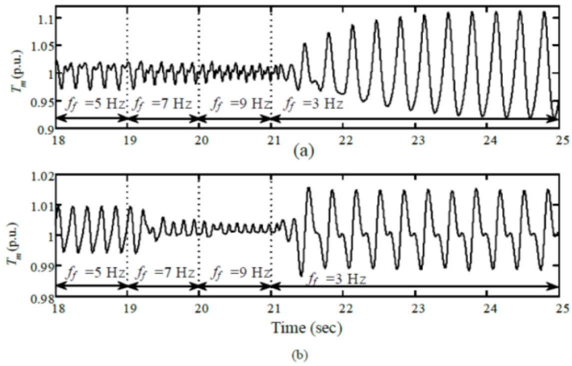

Figure 14: Mechanical torque waveform for (a) initial values; (b) proposed values of controller parameters for different values of f_f

Injection of measured current signal

In this section, the actual current signal measured including wide-bandwidth noise is injected into the system as an electric arc furnace current. In this scenario, the mechanical torque for the initial parameters, K_I = 1, K_P = 55, and the proposed parameters, K_I = 4, K_P= 1, respectively, are shown in Figures 15a and 15b respectively. By comparing these two forms, mechanical oscillations are effectively reduced by using the proposed parameters.

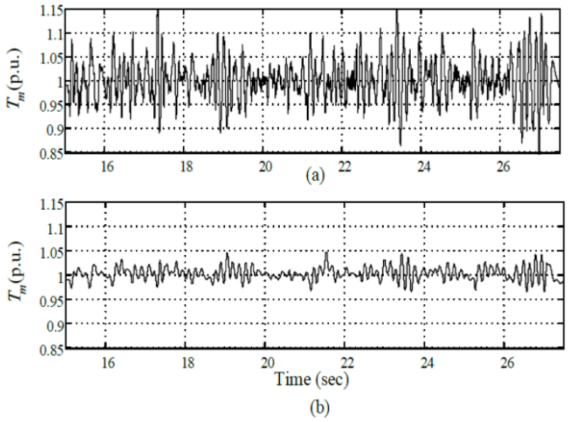

Figure 15: The mechanical torque waveform for (a) the initial values; (b) the proposed values of the controlling parameters in the face of the measured signal

Conclusion

The problem discussed in this article is a real industrial challenge that has occurred in some steel industries of the country. Mathematical analysis and simulation studies carried out in this paper show that the electric power fluctuation of electric arc furnaces causes oscillation of power in a synchronous generator and, as a result, oscillates the mechanical torque. These fluctuations lead to a severe mechanical stress on the synchronous generator and its primary stimulus in the electric arc furnace. The problem in this paper is modeled mathematically and is presented for its implementation. This paper examines this issue by modeling a real network in PSCAD / EMTDC software, which includes small scale synchronous generator and nonlinear arc furnace charge. In the following, the effects of the primary stimulus controller parameters on the small-scale synchronous generator were investigated in different conditions and using indices. Using these parameters, the appropriate values of these parameters were determined.

The studies carried out in this paper resulted in the following results:

1. The proportional factor gain (K_P) must be selected to the lowest possible value so that the number of mechanical oscillations is reduced. The factor integral gain agent (K_I) has little effect on the number of these fluctuations.
2. The value of the integral gain agent (K_I) must be selected as high as possible so that the dynamic performance of the generator is improved in the face of transient states, such as variations in the governor reference.
3. The amount of proportional gain (K_P) must be equal to the minimum value selected to increase the amount of CCT in the face of short-circuit fault.

The parameter has a small effect on the value of this index. According to the above results, the proper parameters of the primary stimulus controller in the studied network were set to be equal to K_P = 0.1 and K_I = 4, and the productive performance was evaluated in different situations. In this paper, in order to exploit the synchronous generator in the vicinity of the electric arc furnace load and to improve the mechanical fluctuations resulting from it, two methods are proposed:

1. Proper selection of generator controller parameters using the proposed strategy in the article.
2. Use of lowpass filter with PI controller.

It is worth noting that both proposed solutions allow the implementation of digital generators. These methods can be simple, feasible, cost-effective and effective.

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