# An Improved Structure of an Adaptive Excitation Control System Operating under Short-Circuit

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*Abstract*—**The paper presents an extended structure for a minimum variance adaptive control system of an induction generator, which aims to improve its operating behavior under electrical short-circuit conditions. The basic design idea is to limit the control to physically achievable values, and thus increasing the robustness of the control system and avoiding an instability regime. A control limiting block is proposed and used for this purpose. Moreover, a short-circuit detector enables an on-line setting of the control penalty factor, improving the quality of the controlled output. All these additional customizations of the control system, implemented to keep the plant operational under and after a short-time short-circuit fault (acting as an abnormal perturbation), must also provide good performance in the normal operating mode.**

*Index Terms*—**adaptive control, control engineering, generators, power system faults, short circuit currents**

## I. Introduction

Although the issue of the self-tuning adaptive control is no longer a novelty, certainly it is still actuality [1-3]. Also, its applicability to power systems is well described in the technical literature [4-8]. A standard procedure is used to design a minimum variance self-tuning controller, regardless of the controlled process. This procedure is based on identification of a linear model which describes the plant functionality around an operating point, assuming minimization of a minimum-variance criterion function that allows the computation of the control law. One such criterion function ensures both a variance minimization of the controlled output error and of the controller output. The minimization of the controller output variance is required in order to generate achievable values for the control, which are physically realizable by a real system (and not only through a simulation) and practically limiting the control to a reasonable range of values. In this regard, a control tuning parameter (commonly named "control penalty factor") is integrated (and properly set) in the criterion function, and implicitly in the resulted control law (indirectly penalizing the control) [2],[9-10].

In a normal operating regime (under action of some reasonable perturbations), an adequate setting of the control penalty factor can ensure the stability of the control system and implicitly its robustness. In the considered operating regime, involving a short-circuit fault at generator terminals, the perturbed output (voltage/current) overflows outside of the usual range [11-12]. Therefore, the process being strongly perturbed, maintaining the control system stability becomes one of the main objectives.

An induction generator with external excitation is considered as controlled process. One or more electrical consumers are connected to the generator terminals (Fig. 1). The control system's objective is to maintain the generator terminal voltage constant by controlling the excitation voltage. This issue is presented in many papers, most of them analyzing a normal operating regime, perturbed by the variation of the mechanic torque or by load/unload conditions (usual perturbations which can produce reasonable variations of the controlled terminal voltage) [4-6]. The short-circuit fault is a strong perturbation that disturbs the induction generator control system. Special safety devices (circuit breaker, fuses or voltage protection circuits) are used in order to switch off the electrical consumer which generates the short-circuit, in order to avoid the possible damages (see Fig. 1) [13-15]. Usually, the circuit breakers do not react to the overcurrent immediately, and often they have a delay time of about 60 ~100 (ms) [16]. Minimum dead time for short-circuit development is often equal to the time delay of a circuit breaker [17]. Basically, the terminal voltage (the controlled output) tends towards zero and such variation of the controlled voltage could lead to the instability of the control system (especially in the case of a long reaction time of the circuit breaker). The paper analyses the operating behavior of the control system during and especially after the short-circuit fault is eliminated by the circuit breakers (disconnecting the fault electrical consumer which causes the short-circuit). The goal of the proposed strategy is to avoid a control system failure as a result of such perturbation.

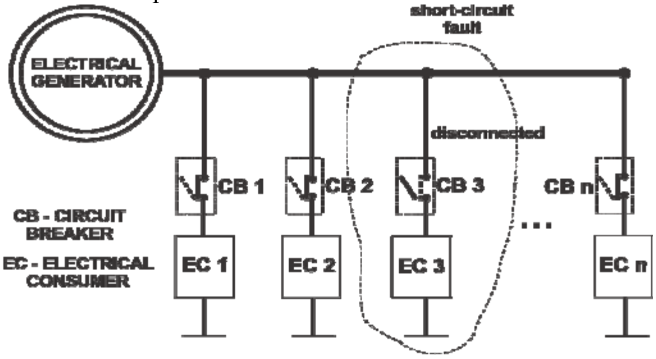


Figure 1. Electrical generator with electrical consumers connected at the terminals

This work was developed through the Partnerships in Priority Areas - PN II, with the support of ANCS, UEFISCDI, Project No. 36/2012, Code: PN-II-PT-PCCA-2011-3.2-1519.

Digital Object Identifier 10.4316/AECE.2016.02006

## II. The Design of the Control Law for Normal Operating Regime

The paper analyzes the design and tuning of an adaptive self-tuning control system which controls the behavior of an induction generator operating under a short time short-circuit conditions, before and after the actions of the circuit breaker (which disconnect the fault consumer). In the context of the above mentioned, the case of a short circuit fault acting for short period of time, called time delay fuses, up to 100 (ms), was analyzed.

The adaptive control system aims to maintain a constant voltage at the induction generator terminals. The plant is disturbed by a stochastic noise with variance $\sigma^2=0.01$, to ensure the excitation of a recursive least square (RLS) parameter estimator (with the forgetting factor $\lambda=0.99$) [18-19].

For all case studies presented in the paper, a nonlinear 7th order model based on the classical *d-q* Park's equations was used for the simulation of an induction generator with electrical consumers connected at the terminals [20-24].

The equations set (1) and (2), describing completely the simulation model implemented in Simulink, are the following one [22]:

a) The initial voltages equations, respectively the motion equation:

$$\begin{cases} R_1 i_{d1} + L_{d1}\dfrac{d}{dt}(i_{d1}) + L_{d21}\dfrac{d}{dt}(i_{d2}) + L_{1h}\dfrac{d}{dt}(i_{d3}) - \omega_1(L_{q1}i_{q1} + L_{q21}i_{q2} + L_{1h}i_{q3}) - u_{ex} = 0 \\ R_1 i_{q1} + L_{q1}\dfrac{d}{dt}(i_{q1}) + L_{q21}\dfrac{d}{dt}(i_{q2}) + L_{1h}\dfrac{d}{dt}(i_{q3}) + \omega_1(L_{d1}i_{d1} + L_{d21}id_2 + L_{1h}i_{d3}) = 0 \\ -(R_2+R_C)i_{d2} - L_{d12}\dfrac{d}{dt}(i_{d1}) - L_{d2}\dfrac{d}{dt}(i_{d2}) - L_{1h}\dfrac{d}{dt}(i_{d3}) + \omega_1(L_{q12}i_{q1} + L_{q2}i_{q2} + L_{1h}i_{q3}) = 0 \\ -(R_2+R_C)i_{q2} - L_{q12}\dfrac{d}{dt}(i_{q1}) - L_{q2}\dfrac{d}{dt}(i_{q2}) - L_{1h}\dfrac{d}{dt}(i_{q3}) - \omega_1(L_{d12}i_{d1} + L_{d2}i_{d2} + L_{1h}i_{d3}) = 0 \\ R_3 i_{d3} + L_{1h}\dfrac{d}{dt}(i_{d1}) + L_{1h}\dfrac{d}{dt}(i_{d2}) + L_{d3}\dfrac{d}{dt}(i_{d3}) - (\omega_1-\omega)(L_{1h}i_{q1} + L_{1h}i_{q2} + L_{q3}i_{q3}) = 0 \\ R_3 i_{q3} + L_{1h}\dfrac{d}{dt}(i_{q1}) + L_{1h}\dfrac{d}{dt}(i_{q2}) + L_{q3}\dfrac{d}{dt}(i_{q3}) + (\omega_1-\omega)(L_{1h}i_{d1} + L_{1h}i_{d2} + L_{d3}i_{d3}) = 0 \\ \dfrac{d\omega}{dt} = (\mathrm{p}\cdot \mathrm{L_{1h}}\cdot(i_{q1}\cdot i_{d3} + i_{d3}\cdot i_{q2} - i_{d1}\cdot i_{q3} - i_{q3}\cdot i_{d2}) + M_m)\cdot p/J \end{cases} \quad (1)$$

b) The connection equations of the induction generator to the consumers through a long transmission line with $\gamma_e$ resistance and $\chi_e$ reactance:

$$\begin{cases} v_d = v_b \sin\delta + \gamma_e i_{d2} - x_e i_{q2} \\ v_q = v_b \cos\delta + \gamma_e i_{q2} + x_e i_{d2} \\ u_t = \sqrt{{v_d}^2 + {v_q}^2} \end{cases} \quad (2)$$

where: ω - rotation speed; ω1 – synchronous speed; Mm – mechanical torque; id, iq – d, q axis currents projections; J – inertia moment; vd, vq - d, q axis terminal voltage's projections; uex – excitation voltage; ut – terminal voltage; vb – network voltage; R1 – stator excitation winding resistance; R2 – stator load winding resistance; R3 – rotor winding resistance; Ld1, Lq1, – d, q axis inductances projections of the stator excitation winding; Ld2, Lq2 – d, q axis inductances projections of the stator load winding; Ld3, Lq3 – d, q axis inductances projections of the rotor winding; Ld12, Ld21, Lq12, Lq21, L1h– leakage /mutual inductance; xe – transmission line reactance; γe– transmission line resistance; p – number of pole pairs; $\delta$ – rotor angle ($\omega = \dfrac{d}{dt}(\delta)$)

The design of the control strategy assumes that the functioning of the generator can be modeled, around a functioning point, by a 4th order discrete transfer function (see relation (3)) [22-23].

$$H(z^{-1}) = z^{-1}\frac{B(z^{-1})}{A(z^{-1})} = z^{-1}\frac{b_3 z^{-3} + b_2 z^{-2} + b_1 z^{-1} + b_0}{a_4 z^{-4} + a_3 z^{-3} + a_2 z^{-2} + a_1 z^{-1} + 1} = \frac{y}{u} \quad (3)$$

where: $y$ – the system output (terminal voltage); $u$ – the controller output (excitation voltage); $z^{-1}$- the shift operator; $a_{1..4}$, $b_{0..3}$ – the model parameters (parameters of A and B polynomials).

Related to the process, when we refer the process parameters, there is not about the physical parameters of the induction generator. The design of a minimum variance control law is based on a liniarised model describing the process around a functioning point. The parameters of this liniarised model are calculated (in fact, estimated) by the recursive least square estimator (RLS estimator). This estimates are used by the control law, based on them being computed the controller output.

Using such linear model of the process (relation (3)), the control law is computed by minimization of the following criterion function (relation (4)) [24-29]:

$$J = E\left\{[y(t+1) - w(t)]^2 + \rho[u(t) - u_r(t)]^2\right\} \quad (4)$$

where: $y(t)$ – controlled output; $u(t)$ – the controller output, $u_r(t)$– the steady state controller output; $w(t)$– the reference, $\rho$ – the control penalty factor; $E\{.\}$– the mean operator.

And of course, the $u_r(t)$ (the steady state controller output) is not priori known. But the $u_r(t)$ control is on-line calculated based on the following reasoning presented below. In the steady state regime, the controlled output tracks the reference):

$$y(t) = w(t) \quad (5)$$

The process can be described around a functioning point by a linearised model (a discrete transfer function, where z-1 is a shift operator):

$$H(z^{-1}) = z^{-1}\frac{B(z^{-1})}{A(z^{-1})} == \frac{y(t)}{u(t)} \quad (6)$$

By substituting $y(t)$) from relation (5) into relation (6), and by noting the steady state controller output with $u_r(t)$, results:

$$A(z^{-1})w(t) = z^{-1}B(z^{-1})u_r(t) \quad (7)$$

Also, in the steady state regime: $z^{-1} = 1$. So:

$$u_r(t) = \frac{\hat{A}(1)}{\hat{B}(1)}w(t) \quad (8)$$

Of course $\hat{A}(1)$ and $\hat{B}(1)$ are estimated polynomials computed by the RLS estimator (noticed that they are not constant), and $w(t)$ are priori known. So the steady state controller output ($u_r(t)$) is practically computed (or estimated) based on the parameter estimations. Therefore, in the designed control law, $u_r(t)$ does not appear explicitly.

Without going into other details of calculation (which are already presented in many other papers, including of the author [3-5]), by minimization of the criterion function (4), the minimum variance control law is thus obtained (see relation (9)):

$$u(t) = \frac{-z[1-\hat{A}(z^{-1})]y(t)}{\hat{B}(z^{-1})+\rho} + \frac{1+\rho\frac{\hat{A}(1)}{\hat{B}(1)}}{\hat{B}(z^{-1})+\rho}w(t) \quad (9)$$

where through ^ was noted the parameter estimations.

Based on the control law described by relation (9), a first study case presents the behavior of the adaptive control system in a normal operating regime, under a perturbation caused by a 10 % increase of the mechanical torque at time t=1 (sec.). As already mentioned, the control system uses a RLS parameters estimator (with the forgetting factor $\lambda=0.99$).

The best results (see Fig. 2.a, b, c) were obtained for a control penalty factor $\rho=0.0001$ (practically, a very small control penalization thereby aiming at an optimal control).

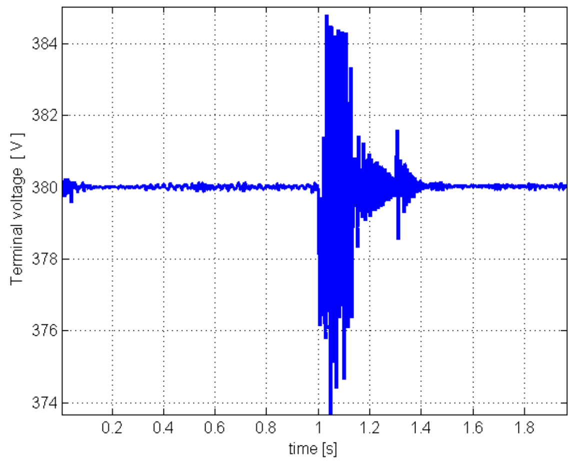


Figure 2.a Controlled output (terminal voltage error) - ρ=0.0001

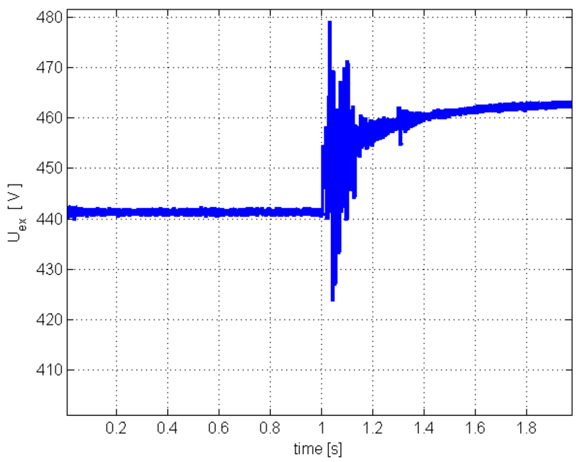


Figure 2.b Controller output (excitation voltage)

There can be noticed a fast rejection of the perturbation (see Fig. 2.a), respectively an acceptable variance of the control (excitation voltage – see Fig. 2.b).

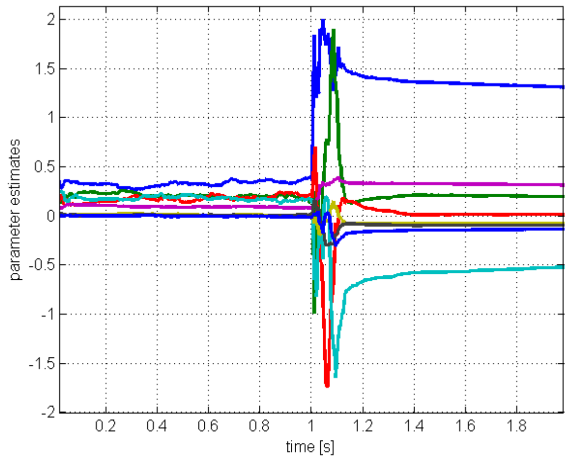


Figure. 2.c Parameter estimations

The purpose of this section is to prove that a proper setting of the controller parameters (the forgetting factor λ and the control penalty factor ρ) for a normal regime can be improper for a short-circuit regime (which strongly disturbs the control system). Although the estimated parameters of the linearised plant model (used by the control law) are continuously variable (being on-line computed by the recursive least square estimator), trying to stabilize the system, this adjustment is not enough. Therefore, a supplementary adjusting of the parameters $\lambda$ or $\rho$ (both of them or just one) must be performed in order to maintain the functionality of the system.

Therefore, in the next study case, for the same controller parameters tuning ($\lambda=0.99$, $\rho=0.0001$), a short-circuit fault (acting during 100 (ms)) was considered occurring at time t=5 (sec.). Analyzing the results presented in Fig. 3.a and Fig. 3.b, there can be noticed that the short-circuit fault has a much bigger effect over the terminal voltage comparatively with the effect of a mechanical torque variation (at time t=1 (sec.)).

Also, it is obviously that the controlled output oscillates (see Fig. 3.b) and the control system becomes unstable. This fact is due to very high control values, practically impossible to reach into a real system (see Fig. 3.c). It pointed out that the parameter estimator preserves its numerical stability (see Fig. 3.d), so the system instability is due to the excessively high values of the control.

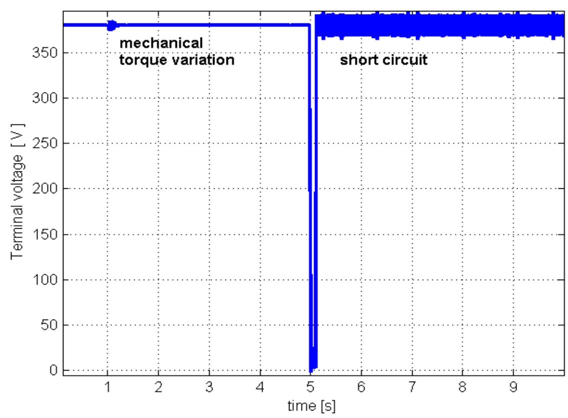


Figure 3.a Controlled output (terminal voltage error)

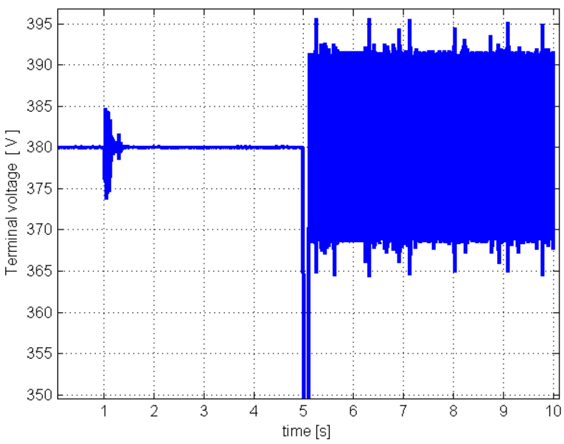


Figure 3.b Controlled output (terminal voltage error) – zoom

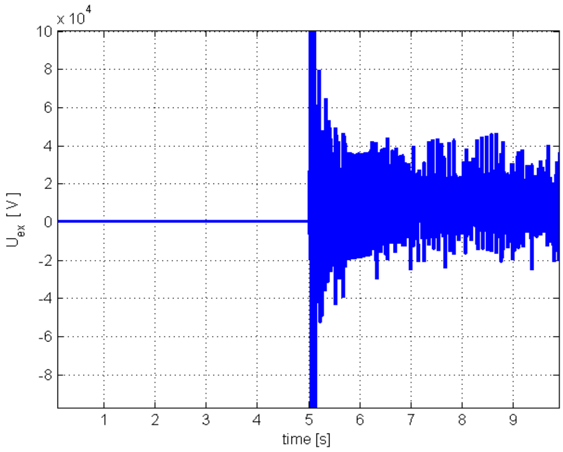


Figure 3.c Controller output (excitation voltage)

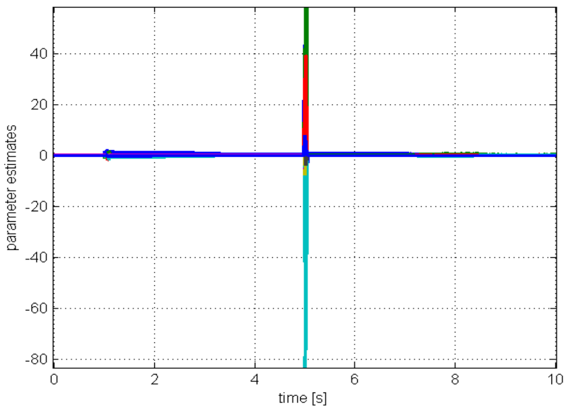


Figure 3.d Parameter estimations

Starting with this observation, it becomes necessary to force a decrease of the controller output. This can be achieved through a direct limitation to a maximum value (by using a limiting block) or through an indirect limitation, by increasing the control penalty factor ($\rho$). Both cases are analyzed further in the paper.

Initially, a significant increase of the control penalty factor ($\rho$) is taken into consideration (from 0.0001 to 0.2). The setting of the new value for $\rho$ is performed when the short-circuit fault occurs (when $Ut \to 0$). At the first sight, by analyzing the response of the control system (see Fig. 4.a), a good result can be observed: after the transient regime (about 2 (sec.)), the system passes again into a stable steady-state, unlike the previous case (Fig. 3.a), when the controlled output oscillates due to the system instability.

Unfortunately, for a short time during the short-circuit fault, very high values of control are obtained through simulation (by four order of magnitude - see Fig. 4.b), which are physically unrealizable. This fact denotes that, for a real implementation, the proposed solution does not solve the problems occurred under a short-circuit fault.

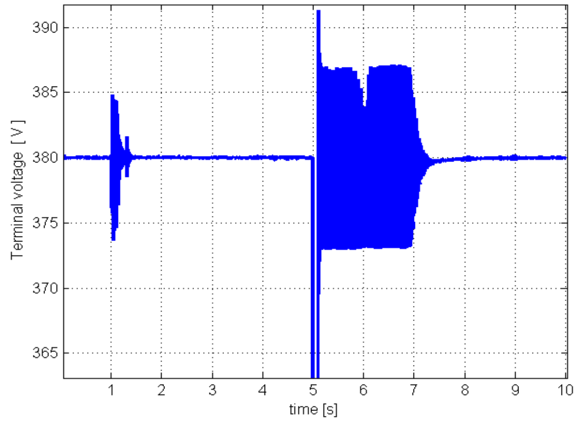


Figure 4.a Controlled output (terminal voltage error) – ρ=0.2

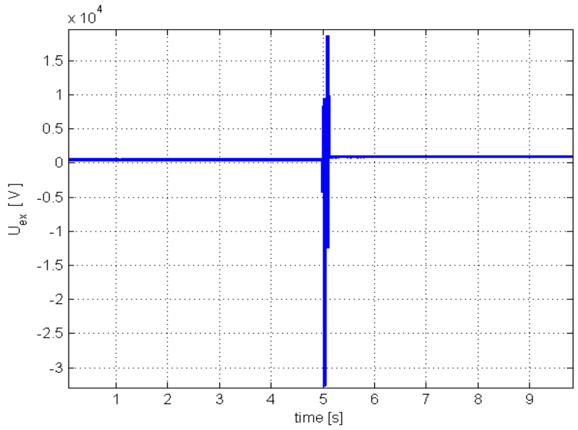


Figure 4.b Penalized controller output (excitation voltage)

Analyzing the second proposed solution (maintaining a constant small value for $\rho=0.0001$), a limiting block for the excitation voltage (in the value range of 0-700 (V)) is proposed (see Fig. 5.b). The obtained results are not satisfactory (Fig. 5.a), the control system becoming unstable under a short-circuit fault. Also, the Fig. 5.c, and 5.d present the parameter estimation under a limited control voltage.

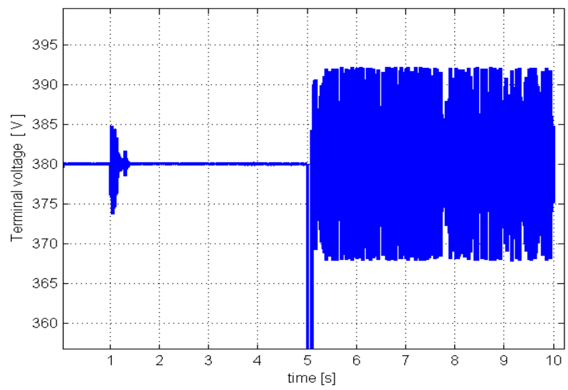


Figure 5.a Controlled output (terminal voltage error) - ρ=0.0001

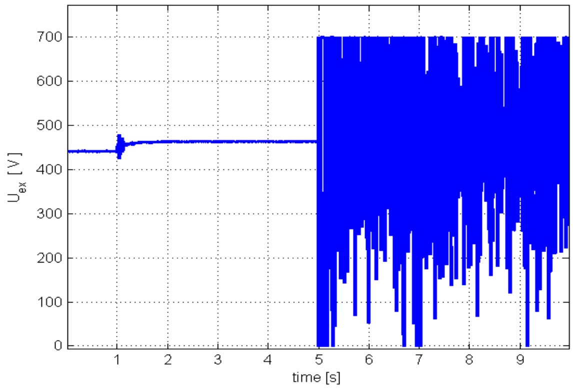


Figure 5.b Limited controller output (excitation voltage)–Uex =[ 0…700] V

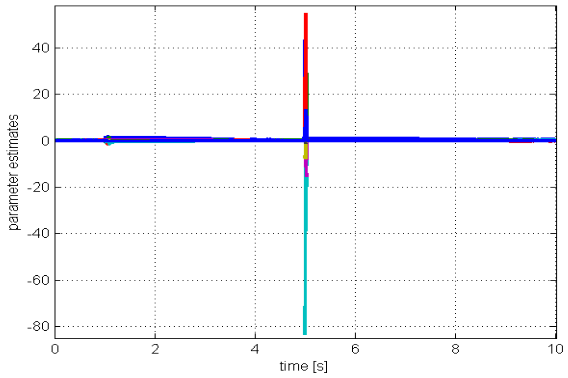


Figure 5.c Parameter estimations

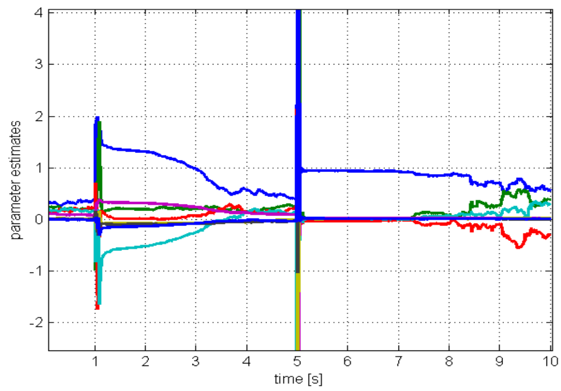


Figure 5.d Parameter estimations –zoom

The only positive aspect is the limitation of the control (but explicitly imposed, by using a supplementary block that forces a limitation). As a conclusion, neither one of the two tested solutions, each of them operating individually, does not solve the occurred problems under such short-circuit perturbation.

## III. Customized Control System for Short-Circuit Fault

Based on previously study cases, the question is: which is the result of simultaneous use of these two actions: the increase of the control penalty factor (*ρ=0.2*), simultaneously with an explicit limitation of the excitation voltage ($U_{ex}$ =*0-700* (V)).

To highlights the novelty of the proposed control structure, in Fig. 6.a is depicted the general structure of a control system based on minimum variance criterion function. The proposed control structure, simultaneously integrating both mentioned actions, is presented in Fig. 6.b.

A simple comparison between these two figures highlights 3 supplementary blocks (additional to the classic structure): a control limiting block, a control penalty factor setting block, which is controlled by a short-circuit detection unit (see highlighted blocks A, B and C from Fig. 6.b). The case study presented below aims a limitation of the excitation voltage (the controller output) and, at the same time, a stabilization of the control system (eliminating the controlled output oscillations).

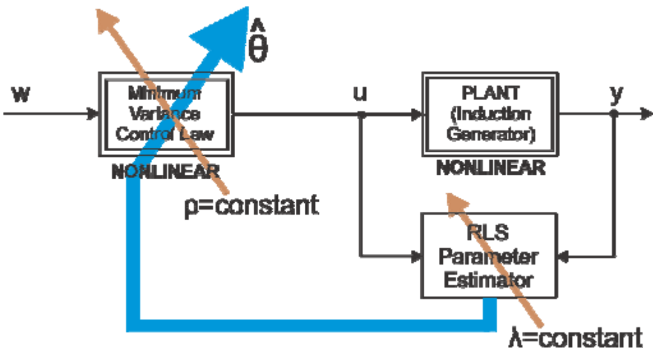


Figure 6.a. The general control system structure

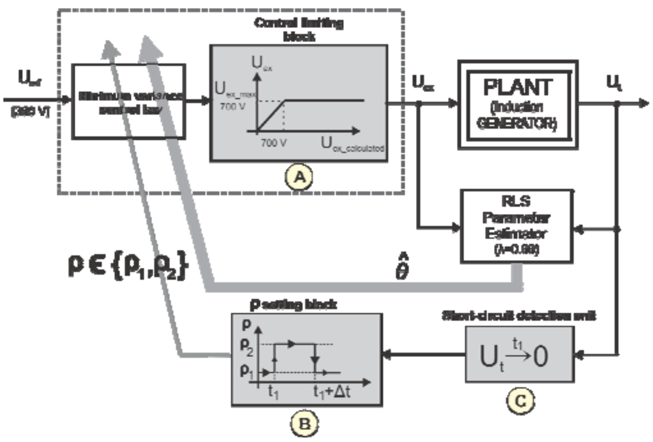


Figure 6.b. The proposed control system structure operating under short-circuit conditions

Beside the control limiting block, an algorithm for switching $\rho$ between two values is proposed ($\rho_1$ -in normal regime, $\rho_2$ - in short-circuit regime), according to the relation (10):

$$\rho=\begin{cases}\rho_1 & -\,small\ value\ when\ t<t_1\\ & \text{(normal regime, no short-circuit)}\\ \rho_2 & -\,high\ value\ when\ t_1\le t\le t_1+\Delta t\\ & \text{(short-circuit regime)}\\ \rho_1 & -\,small\ value\ when\ t>t_1+\Delta t\\ & \text{(end of short-circuit, normal regime)}\end{cases} \quad (10)$$

where: $t$ -time, $t_1$ - time moment when the short-circuit occurs, $\Delta t$ - time interval when short-circuit occurs and for keeping a high value of the control penalty factor.

By substituting the estimated polynomials $\hat{A}(z)$ and $\hat{B}(z)$ with their expressions (see relation (3)) in relation (9), the control law becomes:

$$u(t)=\frac{\hat{a}_1+\hat{a}_2z^{-1}+\hat{a}_3z^{-2}+\hat{a}_4z^{-3}}{(\hat{b}_0+\rho)+\hat{b}_1z^{-1}+\hat{b}_2z^{-2}+\hat{b}_3z^{-3}}\,y(t)+ \\ +\frac{1+\rho\dfrac{\hat{a}_1+\hat{a}_2+\hat{a}_3+\hat{a}_4}{\hat{b}_0+\hat{b}_1+\hat{b}_2+\hat{b}_3}}{(\hat{b}_0+\rho)+\hat{b}_1z^{-1}+\hat{b}_2z^{-2}+\hat{b}_3z^{-3}}\,w(t) \quad (11)$$

It can be observed that $\rho$ is a parameter of the control law, among many another variable parameters. So, $\rho$ can be also variable in according to an algorithm described by relation (10).The technical literature refers an online penalty adaptation, respectively a penalty function, in the context of an adaptive or optimal control [9-10]. The constructive choice of the control penalty function which describes the variation of $\rho$ (relation (10) is one of the paper contributions).

The activation of this algorithm is performed by the short-circuit detection unit (see Fig. 6.b). The short-circuit detection is performed by measuring the terminal voltage, setting a threshold below which, when voltage drops, the short-circuit detection unit controls the setting block of $\rho$, thereby increasing its value.

The results are presented in Fig. 7.a …7.d. Analyzing the Fig. 7.a and the Fig. 7.b, there can be noticed that, after approximately 2 seconds of settling time, the system returns to a stable steady-state. Also, the amplitude of the transient oscillations (of the terminal voltage) is under 4 V (see Fig. 7.b).

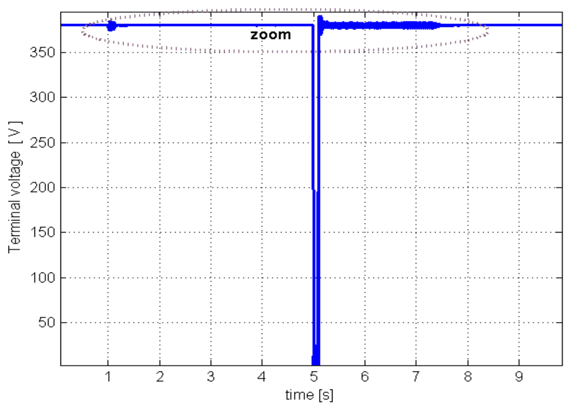


Figure 7.a Controlled output (terminal voltage error) - *ρ: 0.0001->0.2, $U_{ex}$ =[ 0…700] V*

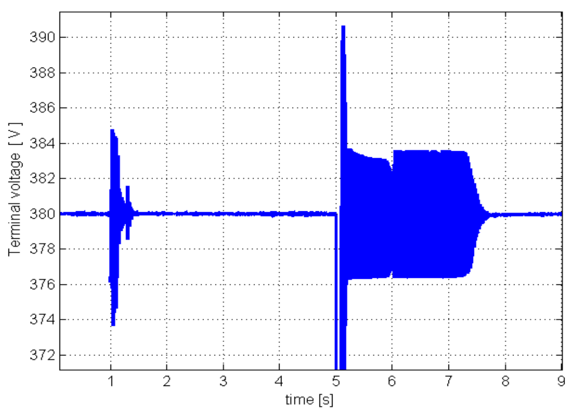


Figure 7.b Controlled output (terminal voltage error)-zoom

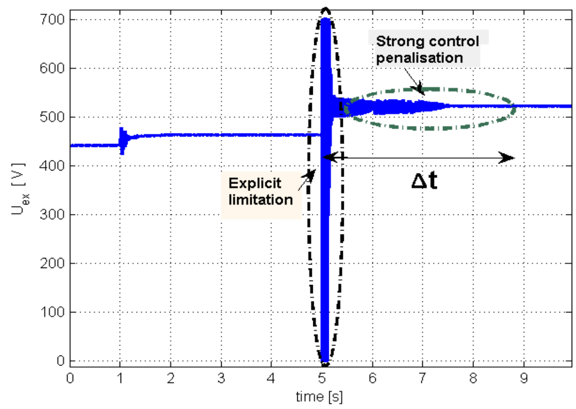


Figure 7.c Controller output (excitation voltage) - ρ: 0.0001->0.2, Uex =[ 0…700] V

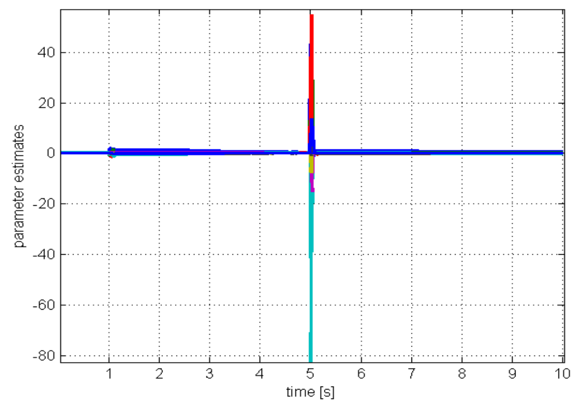


Figure 7.d Parameter estimations

The excitation voltage (the controller output), limited to the value range of 0-700 V during the short circuit fault, returns to a normal steady-state value - about 520 V (after eliminating the short-circuit fault by a circuit breaker). Also, after a preset time interval, in order to ensure the best performances for operating in a normal regime, the control penalty factor returns to a small stationary value close to zero ($\rho$ =*0.0001*). This setting of $\rho$ to the initial default value (proper for a normal regime, but not for short-circuit conditions) produces a small perturbation (see Fig. 8, at time=10 (sec.)), this being the price for keeping under control the negative effects of short-circuits.

It should be noted that, although the two actions (aiming both a control limitation as a main objective) begins and acts simultaneously, their effect is however successive. So, the explicit limitation (using a controller output limiting block) acts effectively only in the first phase of the transient regime (during the short-circuit fault), cutting the huge excitation voltage spikes (see Fig. 5.b or Fig. 7.c).

On the other hand, the strong control penalization (by increasing $\rho$) acts only in the next phase of transient regime (after the end of the short-circuit), ensuring a smoothness of the transient regime, respectively a system stabilization. In the same context, there must be highlighted the time interval (see $\Delta t$ in Fig. 7.c) required for the keeping of a high value for the control penalty factor (a few seconds), before the returning to a small control penalization. The Fig. 7.c presents the successive influence of these actions over the control (and indirectly over the system output).

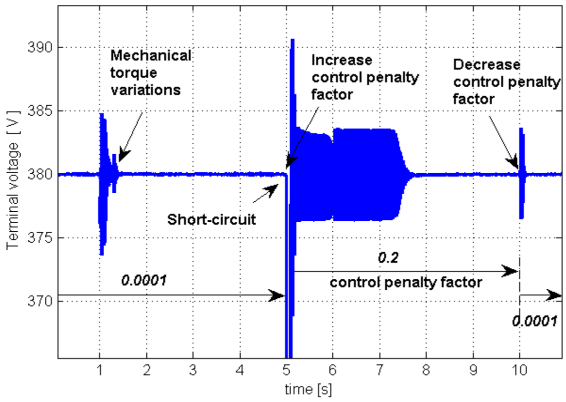


Figure 8. Controlled output (terminal voltage error) - zoom - ρ: 0.0001->0.2->0.0001, Uex =[ 0…700] V

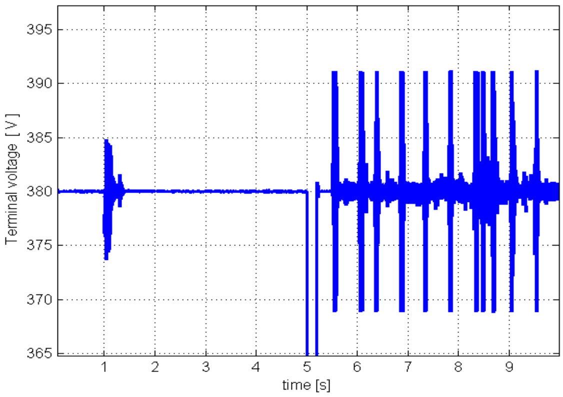


Figure 9. Controlled output (short-circuit time – 200 (ms))

The system was also tested for a longer time short-circuit (however normally in this case, until this time, the circuit breaker should already disconnect the fault consumer, eliminating the short-circuit), but the results are not satisfactory (see Fig. 9, which denotes a system instability). Many other tests (not presented here) are performed for shorter time short-circuits faults, also with good results, completely validating the proposed control strategy. The results of all performed simulation are presented in Table 1 (highlighting the optimal conditions for the best result)

TABLE I. SIMULATION RESULTS

| No | Functioning regime | Control penalty factor ρ | Explicit limitation | Results |
|---|---|---|---|---|
| 1 | Normal | 0.0001 | No | Fast perturbation rejection, acceptable variance of controller output |
| 2 | Short-circuit (100 ms) | 0.0001 | No | Instability due to excessively high values of the control. |
| 3 | Short-circuit (100 ms) | 0.2 | No | Stable, but high controller output |
| 4 | Short-circuit (100 ms) | 0.0001 | Yes | Instability |
| 5 | Short-circuit (100 ms) | 0.2 | Yes | Stable acceptable variance of controller output |
| 6 | Short-circuit (200 ms) | 0.2 | Yes | Instability |

Although the technical literature presents relative numerous control solutions for electric generators, however the number of papers approaching the case of short-circuit conditions is quite limited. Several solutions could be still mentioned, the results being comparable to those obtained in the present work. The paper propose a new approach by considering a variable control penalty factor ($\rho$) and supplementary, an explicit control limitation, unlike other published solutions based on self-tuning with variable forgetting factor, variable gain method, model-based control method etc. (see the references [29-31]). The constructive choice of the penalty function which describes the variation of $\rho$ (relation (10)) is one of the paper contributions. The result depicted in this section prove that solution, based both on explicit limitation, respectively on indirect penalisation of the control can assure the imposed performances for the controlled output.

## IV. Conclusions

A new solution for the design of an excitation adaptive control system for an induction generator operating under short time short-circuit conditions is proposed and validated through numerical simulation. The classical structure of a minimum variance control system, designed by minimization of a criterion function, is properly customized (complemented, more precisely) to solve the problems created by such strong perturbation. Besides the default task of control, the proposed solution must ensure the robustness of the control system, to avoid a possible instability regime. The main cause of the system instability, under such strong perturbations, is the very high computed values of the control (leading to an excessive control, which is physically unrealizable). As a contribution, two additional conditions have been imposed to the classical adaptive control structure: a physical limitation of the control variation (the excitation voltage of the induction generator) by using an explicit limiting block, respectively an on-line tuning of the control penalty factor (activated by the short circuit occurrence). The customized control strategy, validated through numerical simulation, provides good results both in the normal operating regime and also under short time short-circuits conditions.

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