A Novel Coordinated Control Scheme for an Autonomous Self-Excited Induction Generator by using Fuzzy Logic Controller

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Abstract: This project proposes a novel coordination control scheme with flexible controlling ac to-dc converter and a self excitation capacitor bank of a self-administering self-excited induction generator (SEIG) using an electronic signal processor. The purpose of the proposed control arrangement is to keep up the dc voltage at the output terminals of the ac to-dc converter under various working conditions and the system is controlled by using fuzzy logic controller. A three-phase structure show is set up to reproduce the dynamic execution of the considered system.

Keywords: AC-to-DC Converter, Digital Signal Processor (DSP), Renewable-Energy Systems, Self-Excited Induction Generator (SEIG), Switched Excitation Capacitors, Fuzzy Logic Controller.

I. INTRODUCTION

Because of the quick utilization of fossil fuel vitality previously decades, the broad developing ideas on natural security have prompted various examination studies and improvements on different renewable vitality values. As of now, wind vitality is a standout amongst the most develop and promising renewable energy assets in the entire world today. To viably catch accessible vitality from time-changing wind, variable speed wind turbines are by and large utilized. Induction generators (IGs) have gotten to be a standout amongst the most broadly utilized competitors for diverse wind-energy conversion systems (WECSs). Three unique sorts of IG for WECSs can be used: 1) squirrel-confine IG with its stator windings straightforwardly associated to a power grid or encouraged to a power grid through static converters 2) doubly nourished IG with its stator windings specifically joined with a force network and its rotor windings associated to the stator windings through an ac to-dc controlled or uncontrolled rectifier, a dc connection, a dc-to-ac inverter, and a stepup transformer and 3) wound-rotor IG with its rotor windings associated with a variable resistance utilizing a force switch in light of pulse width modulation (PWM). Then again, power electronic converters were additionally proposed to adequately control the output amounts of SEIG. The execution of a few remuneration plans for reactive power and harmonic compensation of SEIGs was exhibited though a hybrid compensation strategy utilizing a silicon-controlled rectifier interfaced to a permanent magnet- generator-based variable-speed control plan was additionally proposed. A WECS interconnected to an utility through an asynchronous connection comprising of a diode-bridge rectifier and a line-commutated inverter was proposed. A rule based fuzzy rationale controller to control the yield power of a PWM-based inverter was introduced, and the goal was to track and concentrate most extreme force from a WECS. The execution of an IG-based framework was enhanced through a voltage-source-based PWM inverter and the electronic converter to accomplish a superior framework conduct on voltaic sources. The arrangement of the state comparison was figured by a suitable numerical system.

Fig 1. Configuration of the studied system.

An ac to-dc converter with dynamic power sifting and power-component redress was proposed and the converter with its ac side inductors and capacitors to dispense with current harmonic comprised of six diodes. Past examination works did not study the coordination control between the exchanged excitation capacitor bank and the ac to-dc controlled converter for SEIGs yet. This project proposes a DSP-based control plan utilizing the rotor velocity of the concentrated on SEIG as an input sign to accomplish coordination control of the switched excitation capacitor bank and the ac to-dc controlled converter.
which are both joined with the stator windings of the considered SEIG. Three rotor-pace working scopes of the SEIG are chosen to actuate the switching capacities for the switching capacitor bank and the controlled ac to-dc converter. Exploratory results got from a research facility 2.2-kW (3-hp) impelling machine driven by a brushless dc motor (BLDC) are additionally performed and thought about with simulated results to approve the adequacy of the proposed control plan.

II. CONFIGURATION OF THE STUDIED SYSTEM

The switched excitation capacitor manage an account with proportional capacitance of $C_f$ is straightforwardly joined with the stator windings of the examined SEIG. The input terminals of the ac to-dc converter are joined with the stator windings of the SEIG through three lines with proportional resistance $R_f$ and proportionate inductance $L_f$. The yield terminals of the ac to-dc converter are sustained to a heap and a dc capacitor of $C_{dc}$. The SEIG is driven by a BLDC engine, which is utilized to reproduce the operation of a wind turbine. The signs of voltage, current, and rotor speed of the examined SEIG are sent to the simple to-computerized converter (ADC) of the DSP. The best possible drive signs of the DSP are utilized to switch the excitation capacitors through the advanced to-simple converter.

![Fig 2. Three-phase connection diagram of the studied SEIG with the switched excitation capacitor bank fed to a three-phase equivalent load.](image)

The PWM signs created by the DSP are utilized to switch the six protected door bipolar transistors (IGBTs) of the ac to-dc converter. The composed programming project of the DSP is downloaded to the DSP’s memory through a RS232-based interface from a PC. The three-stage schematic of the contemplated SEIG with the exchanged excitation capacitor bank nourished to a three-stage comparable burden is appeared in Fig. 2. The identical burden with variable resistance is seen from the information terminals of the ac to-dc converter. The per-unit (p.u.) voltage–current mathematical statements of both stator windings and rotor windings, which are alluded to the Stator-winding side of the studied SEIG, can be expressed in matrix form as follows, respectively,

$$
\begin{align*}
\mathbf{v}_s(abc) &= \mathbf{R}_s(abc)\mathbf{i}_s(abc) + p\mathbf{\lambda}_s(abc) \\
\mathbf{v}_r(abc) &= \mathbf{R}_r(abc)\mathbf{i}_r(abc) + p\mathbf{\lambda}_r(abc)
\end{align*}
$$

where $p$ is the differential administrator as for time ($p = d/dt$); $[\mathbf{v}_s(abc)]$ and $[\mathbf{v}_r(abc)]$ $[\mathbf{i}_s(abc)]$ and $[\mathbf{i}_r(abc)]$ are the p.u. stage voltage (stage current) grids of the three-stage stator windings and rotor windings, individually; $[\mathbf{\lambda}_s(abc)]$ and $[\mathbf{\lambda}_r(abc)]$ are the p.u. flux-linkage grids of the three-stage stator windings and rotor windings, individually; and $[\mathbf{R}_s(abc)]$ also, $[\mathbf{R}_r(abc)]$ are the p.u. corner to corner resistance networks of the three-stage stator windings and rotor windings with $R_s$ and $R_r$ as their corner to corner components, individually. The p.u. flux-linkage grids in (1) and (2) can be communicated in grid structure as takes after

$$
\begin{align*}
\mathbf{\lambda}_s(abc) &= \left[ \begin{array}{c} L_{ls}i_s + & L_{ls}\omega_r & -0.5L_{ls}\omega_r & -0.5L_{ls}\omega_r \\
0.5L_{lm} & L_{lm} & -0.5L_{lm} & -0.5L_{lm} \\
-0.5L_{lm} & 0.5L_{lm} & L_{lm} & -0.5L_{lm} \\
L_{lr} & L_{lr} & L_{lr} & L_{lr}
\end{array} \right] \mathbf{i}_s(abc) \\
\mathbf{\lambda}_r(abc) &= \left[ \begin{array}{c} \cos(\theta_r) & \cos(\theta_r+120^\circ) & \cos(\theta_r+240^\circ) \\
\cos(\theta_r+120^\circ) & \cos(\theta_r) & \cos(\theta_r-120^\circ) \\
\cos(\theta_r+240^\circ) & \cos(\theta_r-120^\circ) & \cos(\theta_r)
\end{array} \right] \\
\mathbf{\lambda}_r(abc) &= \left[ \begin{array}{c} \cos(\theta_r) & \cos(\theta_r+120^\circ) & \cos(\theta_r+240^\circ) \\
\cos(\theta_r+120^\circ) & \cos(\theta_r) & \cos(\theta_r-120^\circ) \\
\cos(\theta_r+240^\circ) & \cos(\theta_r-120^\circ) & \cos(\theta_r)
\end{array} \right]
\end{align*}
$$

Where $L_{ls}$ and $L_{lr}$ are the p.u. spillage inductance of stator and rotor windings, individually; $L_{lm}$ and $L_{mr}$ are the p.u. shared inductance of stator and rotor windings, individually; and $\theta_r$ is the edge in the middle of rotor and the reference casing of the SEIG. The p.u. mechanical torque mathematical statement of the SEIG can be composed as takes after

$$
\begin{align*}
(2H)p(\omega_r) &= T_m - T_e - B\omega_r \\
(1/\Omega_p)p(\omega_r) &= \omega_r
\end{align*}
$$

Where $\Omega_p$ is the p.u. output voltage of the SEIG.

![Fig 3. Characteristic curves of $C_{min}$ versus or under various output voltages of the SEIG $G_{in}$.](image)

<table>
<thead>
<tr>
<th>$C_{min}$ (μF)</th>
<th>$G_{in}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.23 μF</td>
<td>180 V</td>
</tr>
<tr>
<td>138.75 μF</td>
<td>200 V</td>
</tr>
<tr>
<td>182.77 μF</td>
<td>220 V</td>
</tr>
</tbody>
</table>

TABLE 1: Eigenvalues (in radians per second) and $C_{min}$ under various rotor speeds

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Where \( H \) is the idleness steady, \( B \) is the p.u. damping coefficient, \( T_m \) is the p.u. mechanical information torque, \( o_b \) the base rakish rate, and \( T_e \) is the p.u. electromagnetic torque. \( T_e \) can be depicted by the three-stage stator-and rotor-winding streams as takes after

\[
T_e = - [I_{s(a,b)}] T \frac{\partial}{\partial \theta_p} [L_{s(a)}] \left[ I_{r(a,b)} \right].
\]  

(9)

The p.u. voltage equations of the load are written as follows:

\[
(L_{t(a)})p(i_{t,a}) - (L_{i(b)})p(i_{r,b}) = V_o - V_b - (r_{t,a})i_{t,a} + (r_{r,b})i_{r,b}
\]

(10)

\[
(L_{s(a)})p(i_{s,a}) + (L_{i(b)} + L_{i(c)})p(i_{r,b})
\]

\[
- V_o - (r_{t,a})i_{t,a} - (r_{r,b} + r_{r,c})i_{r,b}.
\]  

(11)

Since the estimations of the exchanged excitation capacitor bank, the rotor velocity, and the stacking resistance essentially influence the greatness of created voltage of the SEIG, the determination of required least excitation capacitance \( C_{min} \) is conveyed out by utilizing the plans of eigenvalue and eigenvalue affectability distributed. Table I additionally records a couple of complex-conjugated eigenvalues with zero genuine part for each \( C_{min} \), which speak to the definite working condition when the excitation capacitance is equivalent to \( C_{min} \). Fig. 4 demonstrates the three-stage association graph of the stator-twisting terminals of the SEIG with switched excitation capacitor bank sustained to the IGBT-based ac to-dc converter through line channels with proportional resistance \( R_f \) and equal inductance \( L_f \) . The yield of the ac to-dc converter is joined to a heap by means of two dc capacitors associated in arrangement. The taking after inferred little flag model for the six IGBT switches in Fig. 4 depends on a state–space averaging technique to plan a legitimate damping controller for the ac to-dc converter. Accept the three-stage p.u. voltages (p.u. line streams) created by the SEIG are \( e_R, e_S, \) and \( e_T \) (\( i_a, i_b, \) and \( i_c \)). The p.u. voltage comparisons in Fig. 4 can be composed as takes after

\[
\begin{align*}
\text{Fig4. Three-phase equivalent circuit of the ac-to-dc converter connected to the output terminals of the SEIG through line filters.}
\end{align*}
\]  

\[
\begin{align*}
\varepsilon_{st} &= i_R R_f + (L_f)p(i_R) + e_U - (L_f)p(i_S) - i_S R_f \quad \text{(12)} \\
\varepsilon_{st} &= i_S R_f + (L_f)p(i_S) + e_U - (L_f)p(i_T) - i_T R_f \quad \text{(13)} \\
i_R + i_S + i_T &= 0
\end{align*}
\]  

(14)

Rearranging (12) and (14), gives

\[
(L_f)p(i_R) - (L_f)p(i_S) = e_{RS} - i_R R_f + i_S R_f - e_{UV} \quad \text{(15)}
\]

\[
3(L_f)p(i_R) + 2(L_f)p(i_S) = e_{RS} - i_R R_f - 2i_S R_f - e_{UV} \quad \text{(16)}
\]

\[
3(L_f)p(i_R) = - e_{RS} + e_{ST} + e_{UV} - e_{UV} - 3i_S R_f \quad \text{(17)}
\]

\[
3(L_f)p(i_R) = 2e_{RS} + e_{ST} - 2e_{UV} - e_{UV} - 3i_S R_f \quad \text{(18)}
\]

\[
p \begin{bmatrix} i_R \\ i_S \\ i_T \end{bmatrix} = \frac{1}{3L_f} \begin{bmatrix} 1 & 2 & 1 \\ -1 & -1 & -1 \end{bmatrix} \begin{bmatrix} e_{RS} - e_{UV} \\ e_{ST} - e_{UV} \end{bmatrix} - \frac{R_f}{L_f} \begin{bmatrix} i_R \\ i_S \\ i_T \end{bmatrix}. \]
\]  

(19)

\[
(C_f)p(e_{RS}) + (C_f)p(e_{IR}) = i_a - i_R \quad \text{(20)}
\]

\[
(C_f)p(e_{ST}) - (C_f)p(e_{RS}) = i_a - i_S \quad \text{(21)}
\]

\[
e_{RS} + e_{ST} + e_{UV} - 3i_S R_f = 0 \quad \text{(22)}
\]

\[
3(C_f)p(e_{ST}) = i_a - i_S - i_R + 2i_S \quad \text{(23)}
\]

\[
p \begin{bmatrix} e_{RS} \\ e_{ST} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} i_a - i_R \\ i_a - i_S \end{bmatrix} \quad \text{(24)}
\]

\[
p X_1 = A_1 X_1 + B_1 U_1 \quad \text{(25)}
\]

\[
A_1 = \begin{bmatrix} \frac{R_f}{L_f} & 0 & \frac{R_f}{L_f} \\ 0 & \frac{R_f}{L_f} & \frac{R_f}{L_f} \\ \frac{R_f}{L_f} & \frac{R_f}{L_f} & \frac{R_f}{L_f} \end{bmatrix}
\]

\[
B_1 = \begin{bmatrix} \frac{2 i_R}{3} & 0 & 0 \\ 0 & \frac{2 i_S}{3} & 0 \\ 0 & 0 & \frac{2 i_T}{3} \end{bmatrix}
\]

(26)

\[\begin{bmatrix} U_1 \\ X_1 \end{bmatrix} = \begin{bmatrix} e_{UV} \\ e_{UV} \\ i_a, i_R, i_S, e_{RS}, e_{ST} \end{bmatrix}^T. \]

The p.u. voltage equations of the six IGBTs shown in Fig. 4 can be expressed as follows:

\[
e_R = R_f i_R + (L_f)p(i_R) + V_{u0} + V_{on} \quad \text{(27)}
\]

\[
e_S = R_f i_S + (L_f)p(i_S) + V_{u0} + V_{on} \quad \text{(28)}
\]

\[
e_T = R_f i_T + (L_f)p(i_T) + V_{u0} + V_{on}. \quad \text{(29)}
\]

The p.u. voltage over the dc capacitor at the yield terminals of the ac to-dc converter can be communicated as far as \( d^* \) 1, \( d^* \) 2, and \( d^* \) 3 as takes

\[
(C_{dc})p(V_{dc}) = i_R d^*_1 + i_S d^*_2 + i_T d^*_3 \quad \text{(30)}
\]

Where \( d^*_1 = 1 \) (0) if \( Q_1 \) or \( D_1 \) (Q4 or D4) is ON, \( d^*_2 = 1 \) (0) if \( Q_2 \) or \( D_2 \) (Q5 or D5) is ON, and \( d^*_3 = 1 \) (0) if \( Q_3 \) or \( D_3 \) (Q6 or D6) is ON. Combining (27)–(30) yields
The obtained system equations in state-space form can be written as follows:

\[ Z p X_2 = A_2 X_2 + B_2 U_2 \]  \hspace{1cm} (32)

where

\[ A_2 = \begin{bmatrix}
-R_f & 0 & -\frac{d_t}{2} + \frac{1}{2} \sum_{k=1}^{3} d_k \\
0 & -R_f & -\frac{d_t}{2} + \frac{1}{2} \sum_{k=1}^{3} d_k \\
0 & 0 & -R_f - \frac{d_t}{2} + \frac{1}{2} \sum_{k=1}^{3} d_k
\end{bmatrix} \]

\[ B_2 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \]  \hspace{1cm} (33)

\[ Z = \begin{bmatrix}
L_f & 0 & 0 & 0 \\
0 & L_f & 0 & 0 \\
0 & 0 & L_f & 0 \\
0 & 0 & 0 & C_{dc}
\end{bmatrix} \]  \hspace{1cm} (34)

\[ U_2 = [e_s, e_R, e_T, i_0]^T, \text{ and } X_2 = [i_R, i_s, i_T, V_{dc}]^T. \]

The complete scientific model of the contemplated framework has been inferred as above, and the required damping controller and uninvolved components will be composed utilizing a little flag model as a part of the next segment.

III. OUTLINE OF DAMPING CONTROLLERS FURTHERMORE, PASSIVE ELEMENTS

The p.u. load current appeared in Fig. 4 can be composed as

\[ i_o = i_{load} - (C_{dc})p(V_{dc}). \]  \hspace{1cm} (35)

Assuming the studied ac-to-dc converter is a lossless circuit

\[ 3V_{rms}^2 PF = V_{dc} i_o. \]  \hspace{1cm} (36)

Where PF is the data force variable; \( V_{rms} \) and \( i_{rms} \) are the root-mean-square estimations of \( e_R \) and \( i_R \), individually; \( i_{rms} = k_{rms}V_{rms}i_{ref} \) and \( k_{rms} = k_k k_m \); \( k_c \) is the current closedloop pick up; \( k_p \) is the change proportion of a voltage transformer; what's more, \( k_m \) is the increase of a multiplier. The little flag model of every sign can be communicated by, separately, \( V_{rms} = V_{rms} + V_{rms} \) \( i_{rms} = I_{rms} + I_{rms} \) \( V_{dc} = V_{dc} + V_{dc} \) \( i_o = I_o + i_o \) \( I_{load} = I_{load} + I_{load} \) \( i_{ref} = I_{ref} + i_{ref} \). Substituting the above little flag expressions, expecting solidity force consider and ignoring high-request terms, (36) can be revised as a relentless state mathematical statement as takes

\[ 3k_{rms}(V_{rms})^2 i_{ref} = V_{dc} i_o. \]  \hspace{1cm} (37)

Equation (35) expressed in a small-signal form under the \( s \) domain can be derived as follows:

\[ sC_{dc} V_{dc} = i_o - i_{load}. \]  \hspace{1cm} (39)

Equation (39) and (40), the square outline of the concentrated on framework’s voltage controller is appeared in Fig. 5. The utilized parameters appeared in Fig. 5 are \( G_k = 3k_{rms}(V_{rms})I_{ref}/V_{dc}, Z_L = l/(sC_{dc}), G_Z = io/V_{dc}, G_V = 6k_{rms}V_{rms}I_{ref}/V_{dc}, \) what's more, \( G_t = k_p + k_i/s. \) The proposed voltage controller can render satisfactory damping to the considered SEIG under different stacking conditions, and it is executed in the DSP’s programming. Fig. 6 demonstrates the control square outline of the ac-to-dc converter. The dc join voltage \( V_{dc} \) is nourished back to the voltage-control hinder through a low-pass channel and is contrasted and \( V_{dc}(ref) \) to produce a voltage deviation \( V_{dc} \delta \), which is increased with a sinusoidal capacity sin(\( \omega t \)) to produce a sufficient sign for driving the IGBT-based converter. Fig. 7 demonstrates the flowchart of the primary system inside the DSP's product. Two hindrances are utilized for performing exchanging excitation capacitor bank what's more, creating synchronized PWM (SPWM) sign to control the six IGTBs of the ac-to-dc converter, individually. At the point when the primary project enters interfere with 1, the rate criticism signal can be gotten from ADC and after that the required excitation capacitance is computed.
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in hardware, software, or a combination of both. In other words, fuzzy logic approach to problems’ control mimics how a person would make decisions, only much faster. Fuzzy logic allows to lower complexity by allowing the use of imperfect information in sensible way. It can be implemented in hardware, software, or a combination of both. In other words, fuzzy logic approach to problems’ control mimics how a person would make decisions, only much faster.

The fuzzy logic analysis and control methods shown in Figure 9 can be described as:
1. Receiving one or large number of measurements or other assessment of conditions existing in some system that will be analyzed or controlled.
2. Processing all received inputs according to human based, fuzzy “if-then” rules, which can be expressed in simple language words, and combined with traditional non-fuzzy processing.
3. Averaging and weighting the results from all the individual rules into one single output decision or signal which decides what to do or tells a controlled system what to do. The result output signal is a precise defuzzified value.

The following is Fuzzy Logic Control/Analysis Method diagram

IV. SIMULATION RESULTS

IV. FUZZY LOGIC CONTROLLER

Today control systems are usually described by mathematical models that follow the laws of physics, stochastic models or models which have emerged from mathematical logic. A general difficulty of such constructed model is how to move from a given problem to a proper mathematical model. Undoubtedly, today’s advanced computer technology makes it possible; however managing such systems is still too complex. Fuzzy logic allows to lower complexity by allowing the use of imperfect information in sensible way. It can be implemented

Fig 9. Measured (100 V/div., 50 ms/div.) and simulated dynamic waveforms for the studied SEIG under the low-rotor-speed range.
Medium speed

Fig 10. Measured (100 V/div., 500 ms/div.) and simulated dynamic waveforms for the studied SEIG under the medium-rotor-speed range.

Medium Rotor speed

High Speed:

Fig 11. Measured (100 V/div., 50 ms/div.) and simulated dynamic waveforms for the studied SEIG under the high-rotor-speed range.

Stator voltage

Rotor speed

Stator voltage

Rotor speed

Stator voltage

Rotor speed

Fig 13a. Sudden increasing of a resistive load

Fig 13b. Sudden disconnection of a dc motor load.

Fig 14. The SEIG is suddenly switched off at $t = t_1$.

V. CONCLUSION

This project has displayed a novel coordination control arrange between the self excitation capacitor bank and the delineated ac to-dc converter of the SEIG to offer a steady dc voltage at the output terminals of the ac to-dc converter. The required slightest estimations of the exchanged excitation capacitor bank are learned using a united eigenvalue and eigenvalue affectability plan. The proposed coordination control arrange has been executed besides, investigated on an examination office 2.2-kW SEIG driven by a BLDC motor under the different conditions of rotor rate, trading of resistive weight and withdrawal of a dc motor weight, and two-phase voltages information to the ac to-dc converter. The proposed control arrange is to keep up the dc voltage at the output terminals of the ac to-dc converter under various working conditions and the system is controlled by using fuzzy logic controller. The fuzzy logic control scheme has been designed and implemented in an easier and quicker way than a classical integral control method. It can be expected that the proposed
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coordination control arrange between the self excitation capacitor bank and the sketched out ac to-dc converter can be effectively concentrated on SEIG system.

VI. REFERENCES