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An Optimized 2DOF-FOPID Control Scheme Using Fractional Filter for Indirect Matrix Converters in Abnormal Grid Voltage Situations

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Abstract: In order to maintain balanced output voltages and operate at optimal efficiency in the event of an unbalanced grid voltage, the Indirect Matrix Converter (IMC) control is crucial. This work proposes a Two Degree of Freedom Fractional Order Proportional Integral Derivative Control (2DOF-FOPID) system to operate the IMC in the case of an unbalanced voltage condition. To achieve sinusoidal load currents and regulate the input power factor, utilize the IMC. The suggested 2DOF-FOPID-FF control and Enhanced Squirrel Search (ESS) algorithm is used to operate this converter. Then, using the ESS technique, the 2DOF-FOPID-FF control's ideal parameter gains are discovered. Comparing the suggested control technique to the existing algorithms, the findings demonstrate superior transient response with shorter rise time (0.038 sec), settling time (0.207 sec), and no overshoot. The algorithm also converges quickly.

Keywords—*Unbalanced grid voltage, Controller, optimization, matrix converter*

I.Introduction

Ever since its theory was introduced in 1970, matrix converters have been the subject of extensive research [9]. Direct frequency conversion with matrix converters (MCs) has attracted a lot of attention in research lately. This electronic gadget, called a matrix converter (MC), lacks both a capacitor and an inductor, which are large, bulky energy storage elements. The device can function in harsh settings and has a longer lifespan as a result [19]. Both the input and output sides of the converter may accomplish changing amplitude and frequency, and it also has a unitary input power factor and regeneration capabilities. The primary factor driving interest in MCs is its ability to offer a small-footprint solution for a four-quadrant frequency converter, generating sinusoidal input and output currents in a direct current link without the need for passive components. There are drawbacks to not having a dc connection as well: unfiltered input and output disturbances are transmitted over MC, and extra commutation techniques are required to prevent the supply from short-circuiting or the load current channel from being cut [11]. In linear modulation, the output-input voltage ratio is likewise restricted to 0.866. An indirect matrix converter (IMC) can take the place of a traditional space-vector modulated direct matrix converter (DMC) [20]. In addition to having the same advantages and disadvantages as the DMC, the IMC has the ability to lower the line bridge's active switch count to three in the event that bidirectional power flow is not required [21]. Understanding the quality of output power generated by straightforward, practically-implementable open- and closed-loop control techniques of the IMC is crucial.

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The IMC has numerous benefits, including bi-directional power flow, input displacement power factor, and sinusoidal input and output currents as shown in Fig.1[22]. Additionally, the strategies employed for direct matrix converters (DMC) are more complex than the zero *dc*-link current commutation method of IMC [23]. A potential alternative approach for the control strategy of power converters is Model Predictive Control (MPC) [24] [10]. By using the system's mathematical model, this control approach forecasts how the parameters that need to be regulated will behave at each sample time for every valid switching state of the converter. In a cost function, these estimates are compared to a certain reference. The switching state that results in the least amount of error between the forecast and the reference is chosen to be used in the subsequent sampling period. The majority of the latest research on predictive control for IMCs has focused on topologies like three levels, four legs, and other IMC variations [14]. In order to enhance the efficiency of single stage/IMC working under unbalanced grid side voltages, a number of control strategies were presented in the literature. Several dynamic SVM (space vector modulation) strategies are proposed to reduce low-order harmonics caused by unequal grid voltages and to enhance the quality of the grid currents. However, the impact that these techniques might have on output current balance was not discussed in[26].

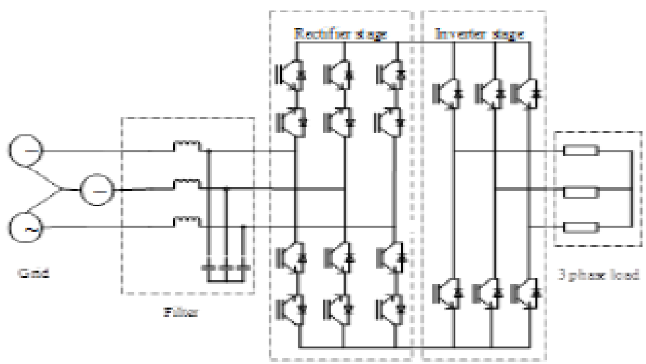

Fig.1: Block diagram of Matrix Converter

Over the past ten years, a number of academics have worked on new topologies derived from matrix converters [17–19], protection schemes, modulation strategies [13], and reliability difficulties such commutation problems. IMC is widely utilised in ac adjustable speed drives, wind energy generation, utility power supplies, and power electronics interface for generation distribution systems as a result of the efforts of numerous researchers [12]. An unique uninterruptible power supply (UPS) is created when a matrix converter is utilised as a utility power supply. The standard space vector modulation (SVPWM) may be applied in a 3-phase three-wire setup [2]. However, in order to maintain balanced output voltages under nonlinear or unbalanced load situations, the 4-leg matrix converter must be utilised to reject the effect of negative and zero sequence load currents [16]. Regarding modulation strategies, the most widely employed modulation techniques include carrier-based modulation, SVM (space vector modulation), and Venturini modulation, which is utilised in the matrix converter industry [25-32].
The purpose of indirect matrix converters is to satisfy the requirements of industrial claims by improving upon matrix converters. During this process, the rectifier regulates grid current signals to create positive DC voltage at its output. The DC voltage is perceived as a virtual entity by an IMC that lacks a capacitor. In phase 2, the inverter transforms direct virtual current (DC) into alternating current (AC). IMC has two main benefits: few clamps are required, and the commutation process is straightforward [5]. IMC is useful in a variety of applications, including distributed generation systems

(DG), multi-phase machines, and multi-phase motors. A number of control strategies have been put forth to enhance IMC performance when operating with unbalanced grid voltages. However, a novel control method is suggested in order to enhance the quality of the input currents and get rid of low-order harmonics caused by grid voltage imbalances.

The main contributions of the research work are as follows:

- The suggested ESS-based 2DOF-FOPID-FF control technique reduces the harmonics, settling time, rise time, and overshoot.
- The 2DOF-FOPID-FF controller's parameter gains are optimized via the ESS algorithm.
- The squirrel search method is improved to speed up convergence.
- The effectiveness of the 2DOF-FOPID-FF controller based on ESS is evaluated in comparison to the current control methodologies

.The subsequent segments are arranged as follows: The literature review is presented in Section 2. The suggested control method is given in Section 3. The results' analysis is given in section 4. The paper is finally concluded in section 5.

II. Literature Review

This section reviews some of the latest efforts made to achieve UPF in the grid.

Regarding the impact of balanced Grid voltage harmonics in an SVM three-phase indirect matrix converter (IMC), M. Jussila and H. Tuusa [1] conducted research in 2017. By employing indirect SVM, the IMC is modified. SVM performance analysis was used to examine how symmetric Grid harmonics affected load voltages and currents. The simulation's outcomes with imbalanced and balanced sinusoidal grid voltages were contrasted with one another.

A new proposed control approach for IMC operating under unbalanced supply voltages was published by M. Hamouda et al. [2] in 2016, with the goal of achieving both balanced output voltages and an input power factor operation that is close to unity. To accomplish flawless tracking of the input reactive power reference, the suggested method first generates an opportune reference current and then designs a PIR controller that is synchronised with the positive sequence of the grid voltages. For the aforementioned reason, a multiple reference frame PLL (MRF-PLL) was put into practise. The next step is to create a real-time estimator of the virtual dc-link voltage with balanced output voltages in mind.

Two approaches have been put out by M. Rivera et al. [3] in 2018 to address this problem by reducing the input filter's resonance. The initial approach was a blend of two techniques: one used active damping, which emulates a virtual resistor in parallel to the input filter's capacitor, and the other involved model predictive current regulation with instantaneous reactive power savings. Using the second approach, the instantaneous reactive power at the input side is reduced by imposing a sinusoidal source current instance. Operating at a fixed switching frequency can improve both approaches even further. The viability of the concept is validated by simulation results, which also show that the system performs better with source and load currents exhibiting a notable decrease in the harmonic distortion caused by the filter resonance.

A novel approach utilising adaptive sliding mode back stepping control for indirect 4-leg MC was introduced by Y. Sun et al. [4] in 2017. Because of the interplay between the input filter and matrix converter, it was resistant to undefined loads and control input disturbance. By analysing the input currents under nonlinear and unbalanced loads, an appropriate input filter to reduce the harmonics entering the electrical system might be designed. Indirect 4-leg MC was given a changing period carrier-based modulation index, which facilitates implementation. Simulations and experimental data confirm that the suggested strategy is feasible. In order to regulate the indirect 4-leg MC with the variable period carrier-based modulation, a reliable adaptive back-stepping technique was put forth. The real load current was estimated using adaptive laws, which responded to the estimation process faster than a general neural network, based on the periodicity of the load currents. The neural network model used for this purpose had a sine kernel function with a known fundamental frequency.

. A predictive control approach was experimentally implemented for a system consisting of two induction machines supplied by a 6-leg IMC in 2015 by M. López et al. [5]. The goal was to assess the method's practical viability in light of its high computing cost and integration of current market technology. With this approach, the immediate input reactive power in the system is minimised while tracking torque, speed, and flux references are achieved on both machines. Along with observations on the experimental setup, execution, and outcomes under balanced and unbalanced grid settings, a theoretical explanation of the key ideas employed in the predictive control technique was provided.

M. Ortega et al. [6] introduced a novel AC-DC-AC matrix converter in 2012. The conventional method for connecting microturbines to the grid, which relied on an inverter-rectifier system (VSR/VSI) with energy storage components, was to be replaced with this matrix converter. A distinct power circuit was presented. There are two stages in the circuit, the second of which was bidirectional. Additionally, a novel switching method utilising two voltage space vectors (VSV) was introduced for the aforementioned circuit. The input voltages (varying frequency) are represented by the first vector, and the output voltages (fixed frequency) by the second. With reference to operational considerations, this approach switching enables changing the VSR/VSI with less loss, at a reduced cost and weight. A Spectrum Digital eZdspTM TMS320F2812 card is one of the components of a laboratory prototype that was created in order to validate the control algorithm. Furthermore, by fuel flow manipulation, the micro-turbine generator's electrical power was regulated via the application of model predictive control (MPC). Big random step changes as well as tiny step changes performed optimally when using the recommended approach.

An approach for low-complexity input current control (LCICC) for an indirect matrix converter running at unity grid power factor (GPF) was reported by Z. Gong et al. in 2019.... In contrast to the traditional approaches that were developed using the d-q synchronous reference frame, the suggested LCICC strategy was established using the stationary coordinate frame. Then, a unique method of controlling input currents was employed, based on the reconstructed grid voltage and current vectors, using the quasi-proportional resonant (QPR) controllers. The suggested approach preserves the benefits of traditional closed-loop control systems while perhaps assisting in lowering control complexity. The trials on a scaled-down prototype verified the suggested strategy's performance in both steady-state and dynamic-state scenarios.

III. ADVANCED 2DOF-FOPID-FF-CONTROL BASED ON ESS DESIGN

The suggested ESS-based 2DOF-FOPID-FF control block diagram is shown in Fig. 2. Double Space Vector Pulse Width Modulation (DSVPWM), input filter, IMC, and controller are the key elements of the proposed control system. The proposed ESS method is used by the 2DOF-FOPID-FF controller, which is in charge of managing the IMC. Among the many advantages of the 2DOF-FOPID controller are set-point tracking, load regulation, and disturbance rejection. Adding a fractional filter will improve the transient response. Furthermore, the ESS algorithm maximizes the benefits of the 2DOF-FOPID parameters. In comparison to the current control approaches, this leads to decreased settling time, rising time, and overshoot. The 2DOF-FOPID-FF controller, which produces the gating pulses for the IMC, outputs to the SVPWM. As an output, DSVPWM produces a gating pulse that controls the IMC. Finally, the IMC is operated using the recommended control technique to achieve UPF functioning.

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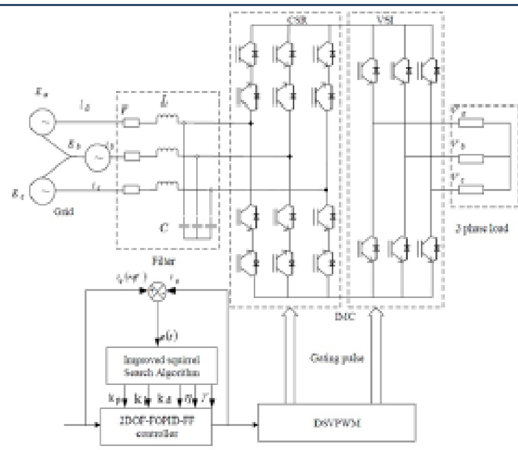


Fig. 2. Block diagram of the proposed ESS based 2DOF-FOPID-FF control technique

A. Enhanced squirrel search algorithm

The ESS algorithm calculates the ideal gain values of the 2DOF-FOPID-FF control parameters such as K_p, K_i, K_d, η and γ are determined by the ESSA algorithm. During the warm months of the year (autumn), squirrels glide from one tree to another in search of food sources. Because the climate is hot enough to meet their daily energy needs more quickly, they eat acorns as soon as they come upon them. Once they have met their daily energy requirements, they start searching for hickory nuts, which are the best food source for the winter. The usual trees without a food source are regarded as the poorest solutions, the top three best solutions are regarded as acorn nuts, and the ideal solution is regarded as a hickory nut. This hierarchy is based on the fitness values of each flying squirrel's location.

(i) Initialization

Flying squirrels (FS) live in forests, and each one's location is represented by a vector. To show the distribution of all flying squirrels, apply Equation (1).

$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & \cdots & S_{1,D} \\ S_{2,1} & S_{2,2} & \cdots & S_{2,D} \\ \vdots & \vdots & \vdots & \vdots \\ S_{k,1} & S_{k,2} & \cdots & S_{k,D} \end{bmatrix} \quad (1)$$

where $S_{m,n}$ denotes the n^{th} dimension of the m^{th} squirrel. Here, the number of dimensions is taken as 5 (K_p, K_i, K_r, η and γ). Equation (a) provides the uniform distribution used to determine the squirrel's beginning location. (2).

$$S_m = S_{low} + (S_{up} - S_{low}) \times U(0,1) \quad (2)$$

where the upper and lower bounds are denoted by S_{up} and S_{low} respectively. $U(0,1)$ denotes a uniformly distributed random number in $[0,1]$.

(ii) Fitness evaluation

The goal is to reduce the fitness (error), as stated in equation (3). If the current solution performs better than the previous one after being evaluated for fitness, the current solution is improved. When the predetermined number of iterations is reached, the process ends. Finally, as the search process terminates, the optimal gain values such a $k_p, k_i and\ k_r$ are obtained.

$$ITAE = \int_0^{\infty} te(t)dt \tag{3}$$

(iii) Update position

Case (i): Flying squirrels that typically feed on acorn nut trees may move to hickory nut trees, which provide the best food source. The new squirrel location in this case can be obtained using the formula provided in Eqn. (4).

$$S_{ac}^{t+1} = \begin{cases} S_{ac}^{t} + G_{dis} \times G_{con} \times \left(S_{hk}^{t} - S_{ac}^{t}\right) & R_{num1} \geq \phi \\ random\ position & otherwise \end{cases} \tag{4}$$

Where ϕ denotes the probability of predator presence which is generally set to 0.1, R_{num1} signifies a random number in $[0,1]$, G_{dis} In order to create a balance between exploration and exploitation, Q stands for the gliding distance and specifies the current iteration. Additionally, this algorithm's exploitation capacity is improved through computation utilising Equn. (5).

$$\phi = (\phi_{max} - \phi_{min}) \times (1 - I / I_{max})^{10} + \phi_{min} \tag{5}$$

where ϕ_{min} and ϕ_{max} represents the minimum and maximum predator presence probability.

Case (ii):

Flying squirrels may migrate in the vicinity of acorn nut trees when they are on regular trees, which do not provide them with food. Consequently, Eqn can be used to calculate the squirrel's new position. (6).

$$S_{nr}^{t+1} = \begin{cases} S_{nr}^{t} + G_{dis} \times G_{con} \times \left(S_{ac}^{t} - S_{nr}^{t}\right) & R_{num2} \geq \phi \\ random\ position & otherwise \end{cases} \tag{6}$$

Case (iii): When squirrels on regular trees (no food supply) have finished eating acorn nuts, they may move to hickory nut trees (best food source) to store the nuts so they can be eaten in an emergency. Equation (7) can be used to calculate the squirrel's new location.

$$S_{nr}^{t+1} = \begin{cases} S_{nr}^{t} + G_{dis} \times G_{con} \times \left(S_{hk}^{t} - S_{nr}^{t}\right) & R_{num3} \geq \phi \\ random\ position & otherwise \end{cases} \tag{7}$$

where R_{num2} and R_{num3} signifies a random number in $[0,1]$.

(iv) Seasonal monitoring

In order to prevent getting stuck in the local optimal solution, ESSA has incorporated seasonal surveillance conditions. Equation is used to model this behaviour using the seasonal constant. (8).

$$M_{const}^{t} = \sqrt{\sum_{n=1}^{D} \left(S_{ac,n}^{t} - S_{hk}^{t}\right)} \tag{8}$$

where $S_{ac,n}^{t}$ denotes the position of the n^{th} squirrel on the acorn tree. The condition $M_{const}^{t} < M_{min}$ is used to check seasonal monitoring. Here S_{min} is computed using Eqn. (9).

$$M_{min} = \frac{10E-6}{(356)^{t/(t_{max}/2.5)}} \tag{9}$$

where t is the iteration and t_{max} denotes the maximum iteration.

A higher value of M_{min} makes exploration easier, whereas a lower value of M_{min} improves the algorithm's capacity to evolve.

(v) Random relocation

The flying squirrels should be moved at random to determine which winter food supply is the best (optimal approach). Equation (i) provides the levy flights of these flying squirrels, which can be used to determine their moves. (10).

$$S_{nr}^{new} = s_L + levy(k) \cdot (s_U - s_L) \quad (10)$$

where s_L and s_U are the lower and upper bounds respectively. $levy(k)$ is exploration of search space.

The search stops when the maximum iteration is reached or when the convergence criteria are met.

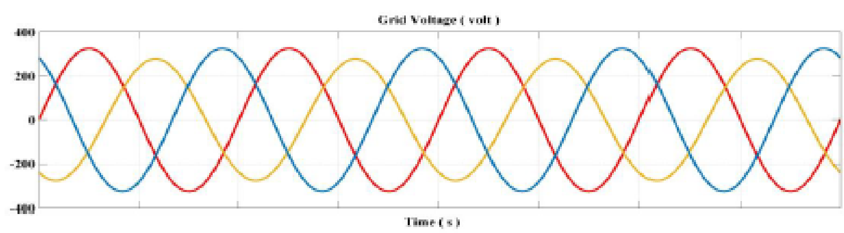
IV. Simulation Result Analysis

The suggested 2DOF-FOPID-FF control method for using the MATLAB/Simulink platform's indirect matrix converter on a machine with a core i7 3.6 GHz CPU and 8 GB of RAM. The input filter has the following values: 100Ω, 9µF, and 0.783mH for resistance, capacitance, and inductance, respectively. Table 1 contains the configuration for the remaining parameters.

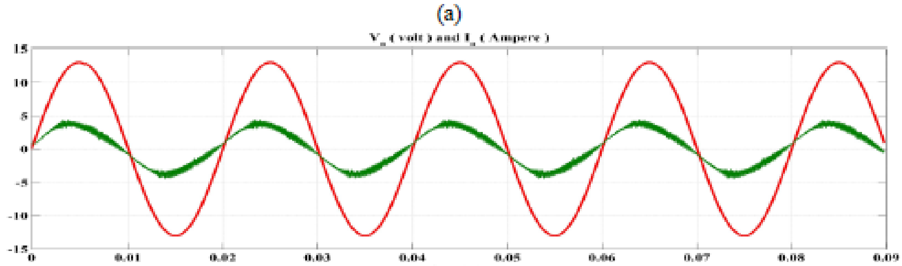
Table 1: Parameter Settings

Parameter	Value	Parameter	Value
Supply line voltage	230 V	load resistance	**100Ω**
Source frequency	50 Hz	Sampling period	200µs
Load frequency	50 Hz	Sampling rate	7.5 kHz
Load inductance	60 mH	Population size	50
Voltage Transfer ratio	0.8	Maximum iteration	100

A. *Comparative analysis*:



(a)



(b)

Fig.3 (a) displays the magnitude unbalanced 3-φ grid voltage and Fig.(b) shows a - phase scaled grid voltage (v_a) and (i_a) under magnitude unbalanced three - phase grid voltage.

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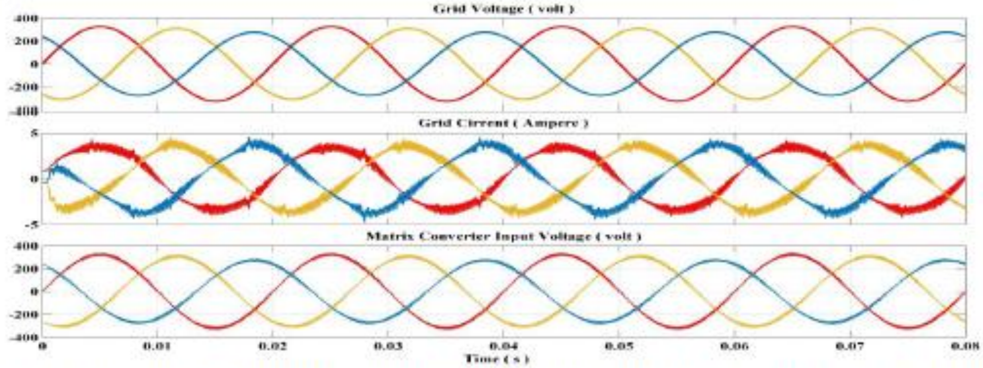
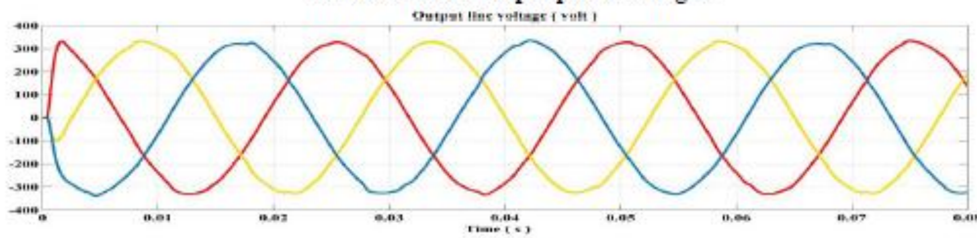
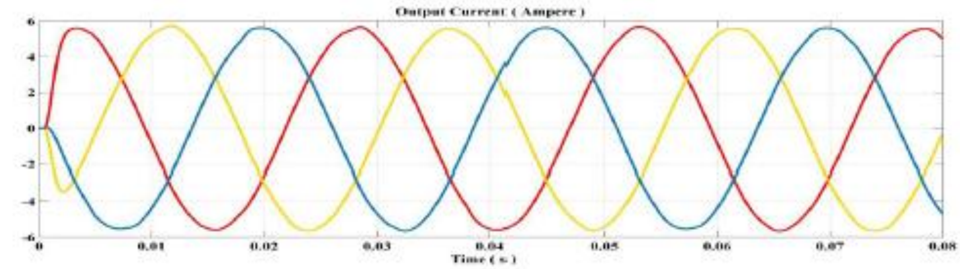


Fig.4: shows the magnitude of unbalanced three-phase grid voltages, Grid phase current and Matrix converter input phase voltages.



(a)



(b)

Fig.5 (a)display the matrix converter output line voltage under magnitude un-balanced three - phase grid voltage and **Fig.**(b) shows matrix converter output line current under magnitude unbalanced three - phase grid voltage.

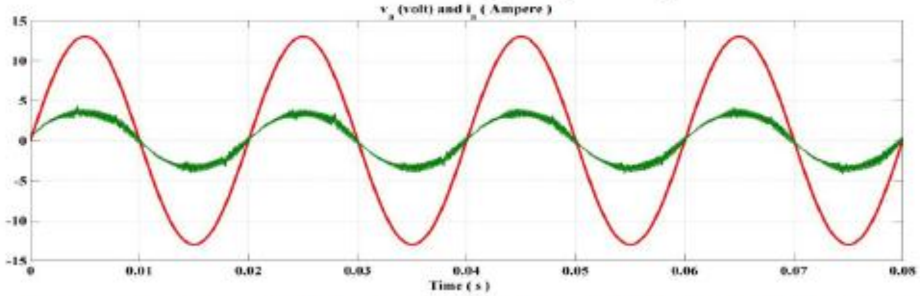


Fig.6 shows a - phase scaled grid voltage (va) and current (ia) under magnitude unbalanced three - phase grid voltage.

By observing waveform Fig.5 and Fig.6 it can be concluded that ESS algorithm-based 2DOF-FOPID-FF Controller is perfectly working under magnitude unbalanced grid voltages, due to which we get near unity power factor and balanced output voltages of matrix converter system.

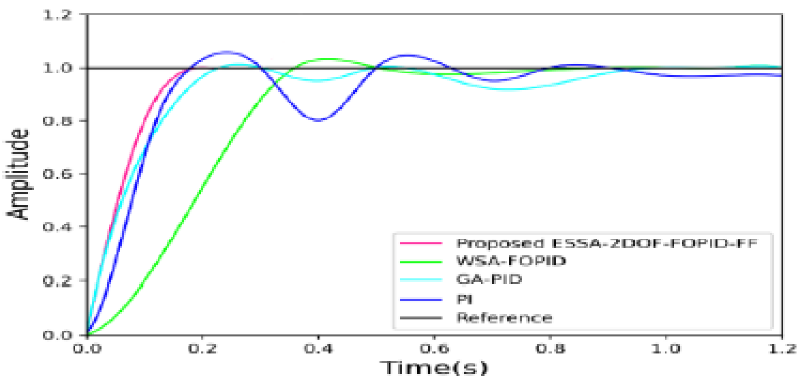


Fig. 7. Transient response analysis

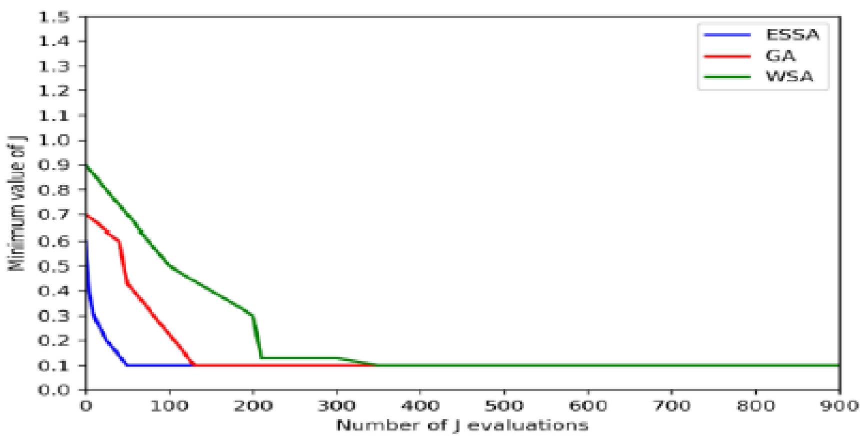


Fig. 8 Convergence analysis

The results confirm that the IMC operates steadily. Furthermore, an almost unity input power factor and sinusoidal input/output currents were obtained. The suggested 2DOF-FOPID-FF controller enhanced IMC input/output properties and decreased distortion when compared to the current PID controller. According to Table 2's data, the suggested method's Total harmonic distortion (THD) is significantly lower than that of the current methods at 1.37%. As a result, even in situations when the grid voltage is imbalanced, ESS-based PIR control functions better. The transient response analysis is shown in Fig. 7. The suggested ESS-algorithm based 2DOF-FOPID-FF control technique has reduced rise time, settling time, and overshoot than the current techniques, such as PI, GA-PID, and WCA-FOPID, as can be seen in the figure. Table 2 offers the quantitative outcomes. A study of the suggested technique's convergence is presented in Figure 9. In comparison to other algorithms like GA and WSA, the results show that the ESS method has a lower level of convergence.

Table 2: Transient Response Characteristics

Control method	Overshoot (%)	Rise time (sec)	Settling time (sec)	THD (%)
PI [30]	1.92	0.103	0.853	1.86
GA-PID [31]	3.64	0.058	0.842	1.51
WCA-FOPID [32]	1.41	0.214	1.120	1.48
Proposed	-	**0.034**	**0.202**	**1.26**

II. Conclusion

This paper proposes a control method for IMC using UPF. By employing a smoother control action, the 2DOF-FOPID-FF controller enhances set-point tracking, load regulation, and disturbance rejection. In addition, the filter's integration shortens the rising, settling, and overshoot times. The ESS algorithm tunes the 2DOF-FOPID-FF controller's parameter gains to perfection. A comparison is made between the performance of the current control techniques and the suggested ESS algorithm-based 2DOF-FOPID-FF control. The suggested ESS algorithm-based 2DOF-FOPID-FF controller performs better, with less overshoot, rising time, setting time, and quicker convergence, according to the results.

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