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DETERMINING THE BEST PERFORMANCE INDICES FOR OPTIMUM CONTROL SIGNAL GENERATION IN A DSTATCOM MODEL

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ABSTRACT

Smart distribution grid can be automated for better power quality (PQ) control by providing additional control strategies to the energy conversion devices such as the distribution static synchronous compensator (DSTATCOM). Appropriate objective function routine is essential in an automated grid for driving the control signals, such that the overall power losses are minimised. In this paper, design procedure of an advanced control strategy for DSTATCOM via model-free-predictive-controller (MFPC) has been proposed. A decision criterion was reached based on combination of performance indices that would generate optimum control signals for the distribution system. Ten indices were paired and simulated in a developed Matlab/Simulink DSTATCOM model. The MFPC based integral time squared error plus the integral time squared error derivative (ITSE + ITSED) paired index produced the desired optimum control signal of 0.0046 radians when compared to manual computer aided design (CAD) and a gradient based computer automated design (CAutoD) methods.

1. INTRODUCTION

The distribution static synchronous compensator (DSTATCOM) has ubiquitously been used to handle power quality (PQ) problems, see for example [1], [2]. However, the traditional computer-aided-design (CAD) control on which it was based would not be suitable for load sensitive smart grid network. Although, the efficacy of the gradient computer-automated-design (CAutoD) method has been demonstrated in [4] there is need to tackle the PQ problem differently through a non-gradient control approach.

Hitherto, the literature was restricted to the use of a single performance index (PI) such as the integral time absolute error (ITAE) in time domain for determining optimum values for control signals. This paper takes a different approach by paring all the known indices namely; integral absolute error (IAE), integral absolute error derivative (IAED), integral time absolute error (ITAE), integral time absolute error derivative (ITAED), integral squared error (ISE), integral squared error derivative (ISED), integral time squared error (ITSE), integral time squared error derivative (ITSED), integral squared time squared error (ISTSE), integral squared time squared error derivative (ISTSED), in both time and frequency domains. The objective is to generate the optimum control signal that would tackle any ensuing power quality (PQ) problem at the distribution corridor.

To this effect, an objective function based on a non-gradient model-free predictive control (MFPC) for DSTATCOM model was developed and simulated in Matlab/Simulink environment. The superiority of the ITSE + ITSED combination was established and validated against the traditional CAD and the gradient (slow) based CAutoD routines

2 MATERIALS AND METHODS

This section presents the materials used in realizing the methods in solving the optimisation problem outlined STATCOM control.

2.1 MFPC direct online design

Figure 1 depicts MFPC signal generator to be implemented in Matlab/Simulink for direct online routine. The simplex version of the iterative feedback tuning introduces the concept of computing a gradient-free cost function in the model-free design. The template of the algorithm in section 2.4 is required for the vector of control parameter to perform online control optimization through gradient extension of Equation 11.

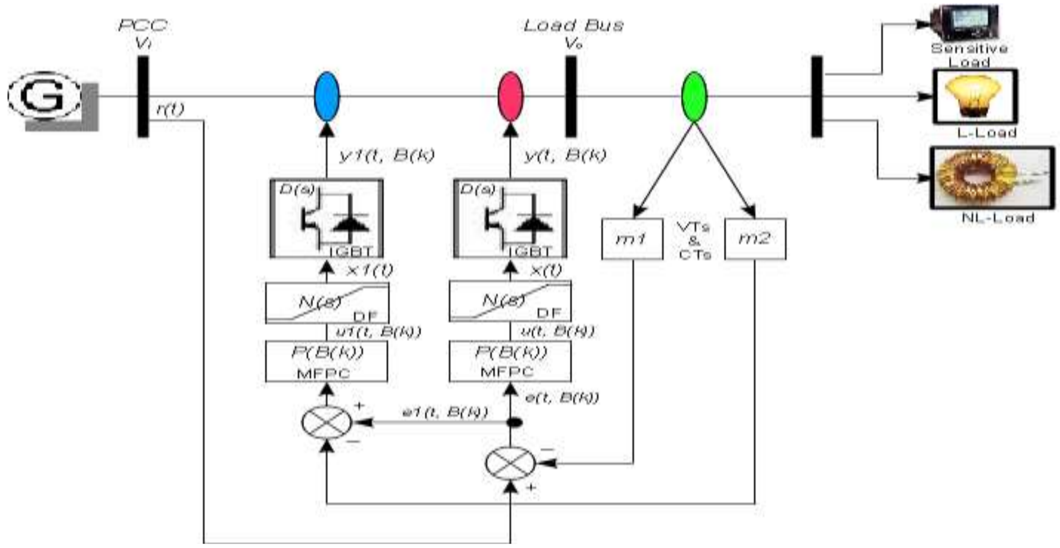


Figure 1: Model-free signal generator

The aim is to compute the closed-loop system signals at varying operating points. This way, real system data is made available to the optimal routine at all time via the database storage formed by the closed-loop signals namely; reference r(t), error e(t), manipulated variable u(t), and the control variable y(t), again prescribed as per Figure 2 in the time domain.

The STATCOM can operate as an inductor when $|V_i| < |V_o|$ or a capacitor when $|V_i| > |V_o|$. But, there is no DSTATCOM action needed in a steady state operation for $|V_i| = |V_o|$. The exchanges improvise for any voltage deficiency that may have been caused as a result of dynamic reactive load demands or systemic disturbances. Despite the lack of active power exchange, a small phase angle still needs be maintained between the ac supply and the DSTATCOM output voltages to replenish the real power component in order to guard against losses [7]

2.2 Describing function premise

Describing functions (DFs) represent a powerful mathematical means for evaluating the behaviour of nonlinear systems [5] DFs make all real systems nonlinear except within a limited operating range. This fact relieves the control engineer from having to linearise nonlinear models for model approximation. The feature is important in tapping DSTATCOM's nonlinearities to generate desirable periodic signals, and determining the stability of illusive nonlinear feedback control systems e.g., fuzzy controllers. In off-line MPC design, stability can easily be achieved through parameter tuning while the problem is being formulated [6]. However, that is difficult in on-line MPC design, especially where model accuracy is paramount. Hence, the online model-free design proposed here uses the capabilities of DFs to sense the presence of limit circles in closed-loop. For MFPC, The same parameters are used in tuning the controller for optimality as in the model-based. The underline assumption being that all linear systems are periodically sinusoidal whose period and amplitude can be predicted by describing functions through a nonlinear feedback system described in Figure 2.

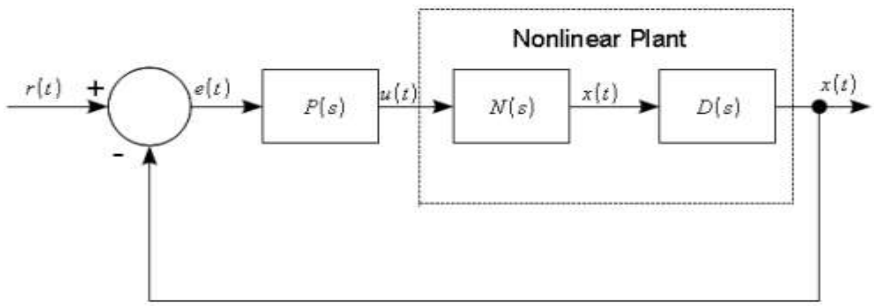


Figure 2: Nonlinear feedback control loop

The figure shows the general notation of a closed-loop control system for nonlinear DSTATCOM plant D(s), augmented with describing function of a saturation element N(s). The decoupled controller P(s) is an unrestricted structure type, e.g., a model based predictive controller generating control cycle u(t) based on error signal e(t), produced by the difference between the setpoint r(t) and the controlled variable y(t).

In this paper, only u(t) and y(t) generated online data is required to implement the model-free predictive control discussed in section 4. It then follows that choosing the error $e = a\cos\omega t$ would simplify extracting the control signal as [6].

$$\mathrm{u} = \mathrm{ue} = \mathrm{u}\left(\mathrm{a}\cos\omega t, -\mathrm{a}\omega\sin\omega t\right) \qquad (1)$$

Since ωt has a minimum period of 2π with e as a trigonometric function, then u is a piecewise smooth function of the same period. Similarly u can be expanded by considering the fundamental component of a Fourier series such that; $u = a_1\cos\omega t + b_1\sin\omega t$.

And ignoring the sub-harmonics and subjecting all the even components to zero, [4].

2.3 Augmented DSTATCOM

The nonlinear DSTATCOM model can be given in the following ordinary differential equations

$$\dot{x} = \mathrm{f}\left(t, x, u\right) \qquad (2)$$

$$y = \mathrm{g}\left(t, x, u\right) \qquad (3)$$

where the variables f and g can be evaluated using any analytical solver, while u and
y are the external control input and output signals to the DSTATCOM.

For the model-free design, all limit cycles in linear systems are assumed to be periodically sinusoidal whose period and amplitude can be predicted by describing functions through the nonlinear feedback control system described above. This assumption is only valid since the transfer function of the nonlinear plant D(s) is a low pass filter of reasonably small time constants, actually less than 0.008 seconds.

The augmented DSTATCOM model based on the ongoing can be represented as a saturation nonlinearity which has the following sinusoidal input describing function by Equations (4), (5), and (6).

$$N\left(a, \omega\right) = -1, \text{if } \omega \le \text{-1} \qquad (4)$$

$$N\left(a, \omega\right) = \frac{2}{\pi}\left(\sin^{-1}\left(\omega\right)\right) + \left(\omega\sqrt{\left(1-\omega^2\right)}\right), \text{if -1} < \omega < \text{-1} \qquad (5)$$

$$N\left(a, \omega\right) = 1, \text{if } \omega \ge 1 \qquad (6)$$

where ω = 0.5/a, defined over saturation within the range of 0.5 and -0.5, and a is the amplitude of the sinusoidal input.

The sine input describing function (SIDF), N(a, ω) can now be computed for any varying range of amplitudes x against the frequency ω, as in Figure 3 which shows a decaying frequency with amplitude growth using the range from 0.1 to 21, at step size of 2.1.

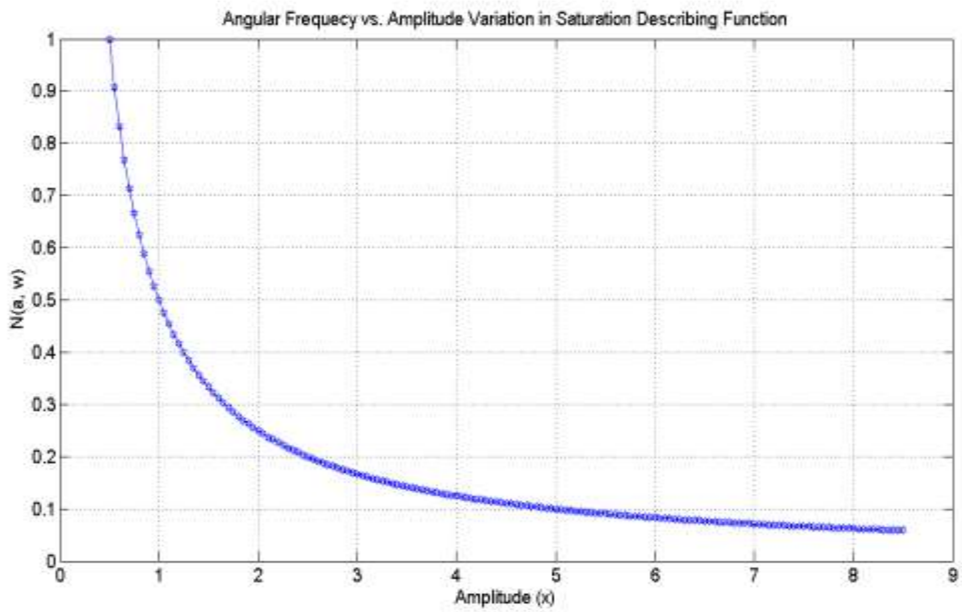


Figure 3: DF of frequency vs amplitude

Note the expression SIDF, is just a modification of the linear transfer function representing the LTI system G(jω) as an approximated quasi-linear system whose response to sine wave is not purely sinusoidal.

In this type of system most of the output energy is assigned to the same frequency (ω) as in the input. Therefore, does not require the customary external harmonic filter as they intrinsically tend to behave like a low or band-pass filter. For this advantage, SIDF technique is invariably applied in estimating oscillation (limit cycle) amplitudes in sinusoidal electronic circuits. Generally, DF methods are more important in the analysis of systems which are not too nonlinear, such as the DSTATCOM.

The condition for the existence of a limit cycle in the system's response is defined in [1] as

$$G(j\omega) = -P(j\omega)D(j\omega) = \frac{-1}{N(a)} \qquad (7)$$

And

$$G(a,\omega) = N(a,\omega)D(j\omega) = -1 \qquad (8)$$

This satisfies the condition for the closed-loop system from Figure 3 to oscillate, assuming a linear and steady state stable. In such case, the system is behaving as a low-pass filter in which the equation is used to predict self-oscillations. The stability analysis of this kind of system may be described as:

Equation 7 can be solved analytically and it is easy to determine the presence of a limit cycle that causes instability at each intersection of the right and the left hand terms of the equation using Nichols curve. The right hand term gives the amplitude of the limit cycle which depends on the saturation droop, while the left hand term gives its frequency that is independent of the droop size. The describing function maps between the lines, irrespective of the droop size, at (0dB, -180) and (1, -180) as illustrated by the Nichols chart in Figure 4.

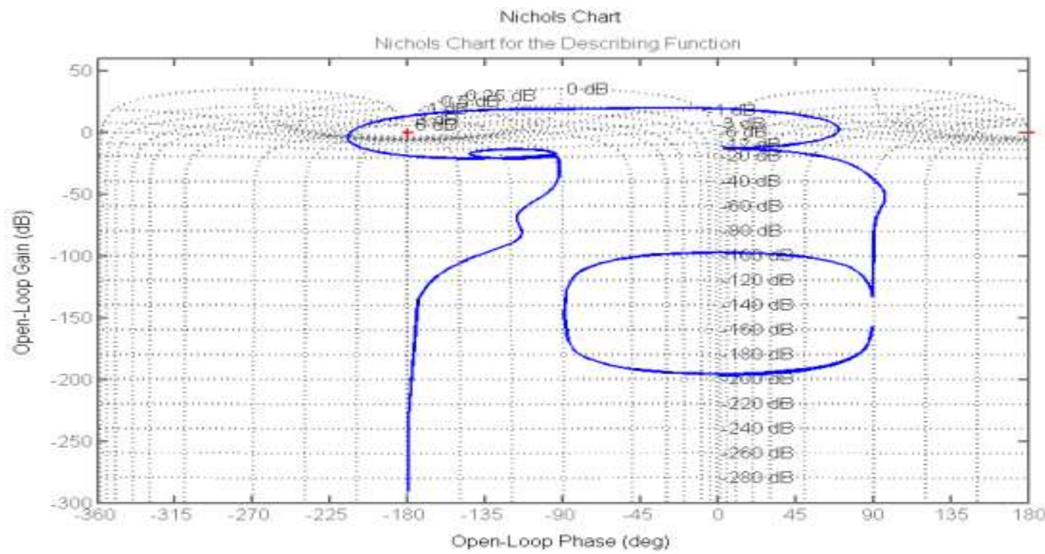


Figure 4: Nichols chart for describing function

Thus, existence of limit cycles is not affected by changes in droop size. But changes in time constants due to, for example, load recovery time can significantly affect P(jω) which is a "gain" value, by longitudinally shifting G(jω) across the Nichols chart. Moving the curve below (0dB, -180) inevitably changes the amplitude and removes any limit cycle present without altering the stability of the closed-loop system.

2.4 Non-gradient optimisation criterion

The decision about optimisation criterion is the second step, which was initially performed through gradient information based cost functions for solving optimization problems since the 1960's Hsu and Meyer (1968). This technique works best in slow processes with large time constants. Since high speeds are particularly desirable in systems with small time-constants, and with continuous shifting operating points. Then, a robust direct optimization criterion is required to access an established database regardless of gradient information to solve the online optimization problem. The simplex algorithm is a direct search method proposed in the next subsection to perform online synthesisation of the controller properties, as a final step to the new model-free design procedure.

To better understand the inner working of the scheme, we first analyse the algorithm through a working template given in Figure 5. The Figure describes a basic deterministic objective function routine ideal for localising weighting indices for error, control, and process output signals expressed in the continuous time domain as

$$J(\beta)=\frac{1}{2T_f}\int_0^{T_f}\left[R_y e(t,\beta)^2+\mu^2 S_u u^2(t,\beta)^2\right]dt \qquad (9)$$

where *R* and *S* are weighing filters, *Tf* is the final time, *t* is time instant, *e* is the system error, *δe* is rate of change of the error, u being the control signal, δu is the rate of change of the control signal, μ is the weighting cost, and β is the vector of control parameters as given in the following equations.

$$J(\beta) = \frac{1}{2T_f}\int_0^{T_f}\left(e^2(t,\beta) + \mu^2 u^2(t,\beta)\right)dt \qquad (10)$$

This formulation leads to the generation of four control parameters based on the vector:

This formulation leads to the generation of four control parameters based on the vector:

$\beta \in \Re^l$ Shown to achieve a steady state as $T_f \to \infty$ in the following manner:

$$\frac{\delta J}{\delta\beta} = \frac{1}{T_f}\int_0^{T_f}\left\{e(t,\beta)\frac{\delta e(t,\beta)}{\delta\beta} + \mu^2 u(t,\beta)\frac{\delta u(t,\beta)}{\delta\beta}\right\} \qquad (11)$$

Details of which can be found in, Bukata BB and Li Y (2012).

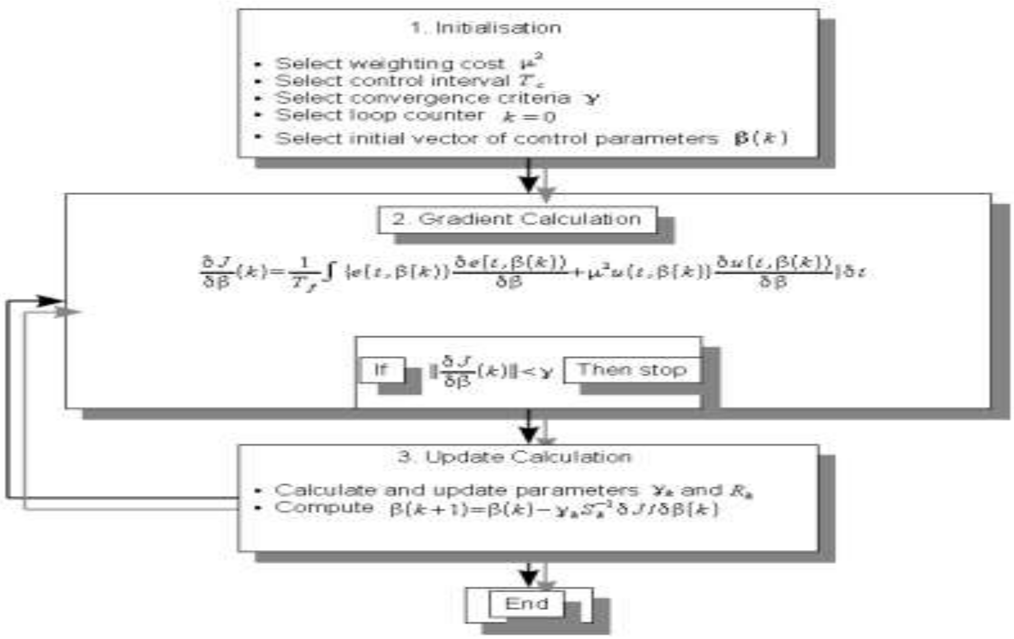


Figure 5: Basic non-gradient optimization routine

3. Results and Discussions

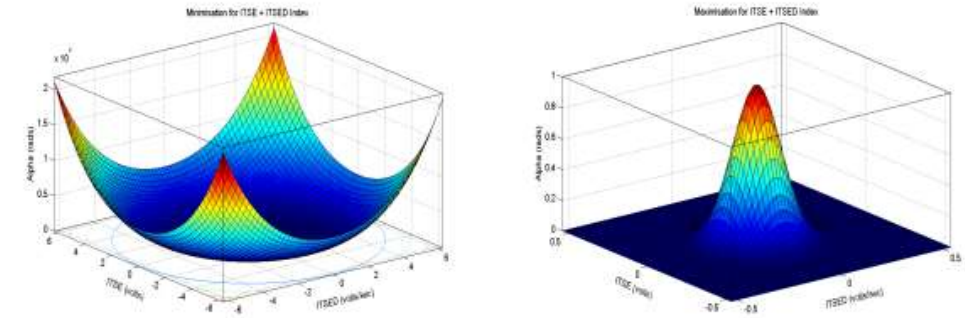
This section presents and discusses the results so far obtained from the outlined methods. Its advantages over other time domain techniques is also highlighted and compared.

3.1 Performance decision criteria

The 3-D plots shown in Figures 6 to 10 compared the **various performance indices** investigated as a matter of decision criteria. The choice of a derivative enhanced ITSE was informed as a broad index for this

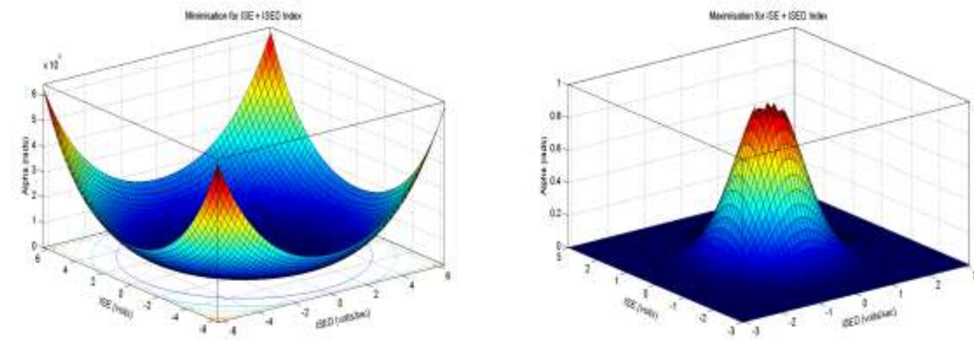
design application, produced through MFPC routine. Its superiority has been demonstrated in Figure 6, where the minimisation and maximisation criteria are both depicted as being complete, and tagged as "satisfactory and suitable in Table 1", when compared to the performances of ISE and ISTSE in Figures 7 to

12, which were produced through CAD and CAutoD techniques, and tagged as unsatisfactory and unsuitable as in Table 1.



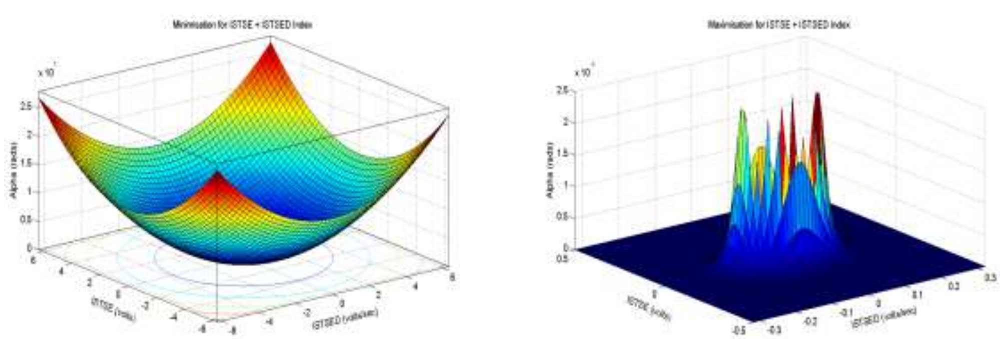
(a) Minimisation (b) Maximisation

Figure 6: ITSE + ITSED performance



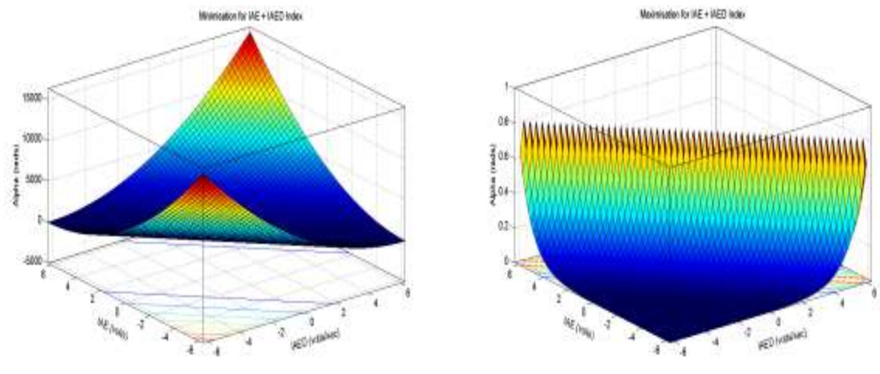
(a) Minimisation (b) Maximisation

Figure 7: ISE + ISED performance



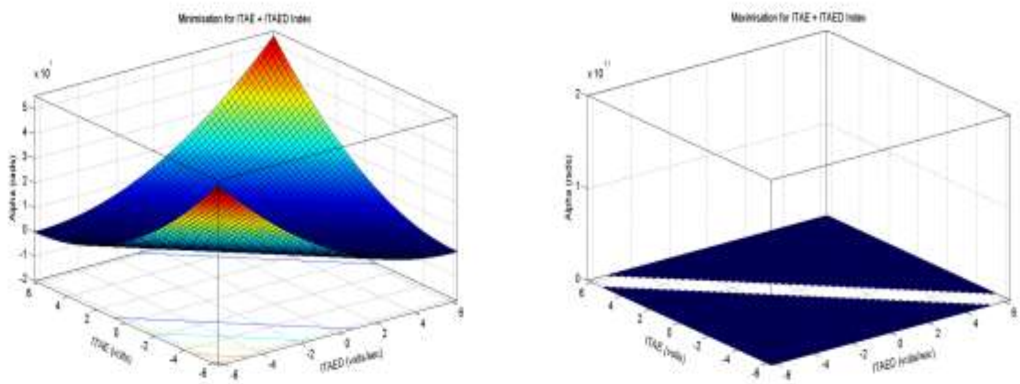
(a) Minimisation (b) Maximisation

Figure 8: ISTSE + ISTSED performance



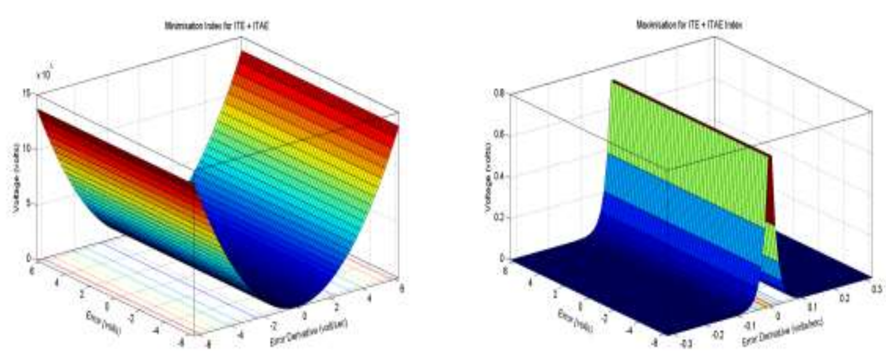
(a) Minimisation (b) Maximisation

Figure 9: IAE + IAED performance



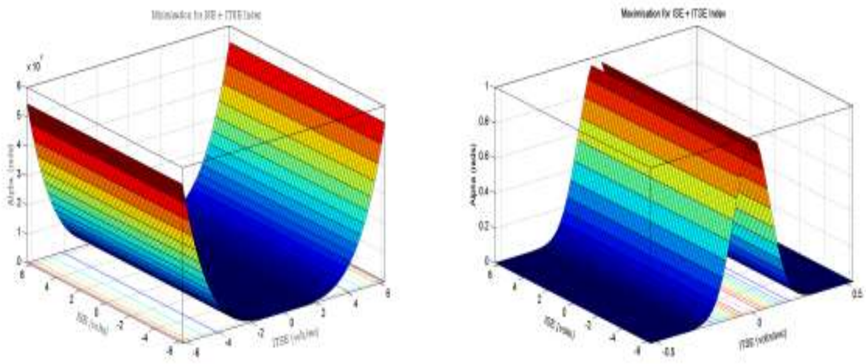
(a) Minimisation (b) Maximisation

Figure 10: ITAE + ITAED performance



(a) Minimisation criteria (b) Maximisation criteria

Figure 11: Time domain correlation of: *e* and _ *e* with respect to *α*



(a) Minimisation criteria (b) Maximisation criteria

Figure 12: Frequency domain correlation of:
e and _ e with respect to α

The deficiencies from these indices are manifest following a vividly accomplished minimisation criterion, where the maximised function failed to reach its unit value, portraying irregular finishing as in an "errupted volcanic surface". Conversely,

Figures 9 and 10 showing respective representation of both IAE and ITAE indices comparing even woefully in both criteria, where the minimisation envelope could not be established, with failings in the maximisation function ending in a "comb structure" or "flattened" surface. These surfaces are a good representation of poor system stability, and hence unsuitable for stable control formulations. A summary of this comparison is given in Table 1.

Table 1: Summary of index performances

P/I	Sensitivity	Minimisation	Maximisation	Applicability
ITSE	$1.751e-009$	Satisfactorily	Satisfactorily	Suitable
ISE	$-3.42e-006$	Satisfactorily	Unsatisfactorily	Unsuitable
ISTSE	$-5.39e-005$	Satisfactorily	Unsatisfactorily	Unsuitable
IAE	$2.251e-007$	Unsatisfactorily	Unsatisfactorily	Unsuitable
ITAE	$3.002e-008$	Unsatisfactorily	Unsatisfactorily	Unsuitable

4. Conclusion

This paper presented a non-gradient control algorithm for online routine interaction in DSTATCOM structural model. The performance of the algorithm was tested and validated against both convention computer-aided-design (CAD), as well as a gradient based computer-automated-design (CAutoD) techniques. Ten paired performance indices (PI) were tested in both time and frequency domains in order to establish which of the indices would produce the optimum control signal that will best in tackling power quality (PQ) problems at the distribution corridor.

The system design procedure was carried out and simulated in Matlab/Simulink environment. The results showed that the performance of ITSE + ITSED index produced a perfect minimum/maximum curve for the control signal at 0.0046 radians to be effective.

It is finally observed that, in the frequency domain, the designer has the advantage of taking control over the system's bandwidth and certain measure of the system's response to unwanted noise and disturbances. While, adding the time domain builds up the missing link between frequency response and a corresponding transient response needed to practically ease tuning through chosen design criteria.

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