Real-Time Implementation for the Robust Controller of the Switched Boost Inverter within an Autonomous Modified Nanogrid

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Abstract: SBI stands for switched-boost inverter and is a single-stage power converter used to connect low-power sources, such as solar photovoltaic (PV) arrays within a modified nanogrid, to loads. Despite its many benefits, such as the fact that it does not require expensive sophisticated dead-time circuitry, its duty ratio is limited to between 0 and 0.5. As a result, this publication is a contribution towards improving the SBI's performance for use in a modified nanogrid. Furthermore, it also presents a revolutionary strategy for a simple closed-loop control technique that overcomes the majority of inverter shortcomings and system nonlinearity. The suggested robust controller uses a metaheuristic optimization technique, called gorilla troops optimization (GTO), to optimize the performance of this controller. The robustness of the suggested controller is tested against the sudden change of the nanogrid input voltage (i.e., PV-voltage), modulation index of the inverter, and the step-change in DC-link output voltage of the inverter. The test results obtained from Matlab/Simulink software are compared with particle swarm optimization (PSO) – as another optimization algorithm. Furthermore, the proposed system is experimentally implemented with OPAL RT-4510v real-time hardware in the loop (HIL), rapid control prototyping, OP-8660 HIL controller and data acquisition platform.

Key-Words: Autonomous Microgrid, Optimization of Gorilla Troops, Hardware in the Loop (HIL), Modified Nanogrid, Real-Time Emulation, and Switched Boost Inverter (SBI).

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1 Introduction

Traditional power inverter topologies such as voltage source inverters (VSI) and current source (CSI) have some limitations [1]. They have some conceptual and practical constraints. They can cover only the DC power to an AC power (since they operate in a bucking or boosting mode) [2]. In addition, the noise problem is induced by electromagnetic interference (EMI). Both switches in the same limb cannot be turned on instantaneously in both VSI and CSI inverters [3]. These classical inverters can be used in traditional nanogrids. A novel modified form of an inverter was created called a switched boost inverter (SBI) [3]. It overcomes the constraints of both traditional VSI and CSI inverters. SBI is really a revolutionary power conversion architecture with unique characteristics. The buck-boost feature of the SBI allows it to generate both DC and AC output voltages simultaneously from the same DC input voltage. SBI can create any required output DC and AC voltage levels even higher than the input DC source voltage, by setting the right shoot-through duty cycle and modulation index. These benefits could not be achieved with traditional VSI. To use the shoot-through states for voltage boost, the inverter pulse width modulation (PWM) control must be modified as discussed in [4]. This will be accomplished by utilizing a switching state known as the shoot-through state, which is not authorized in the VSI. When both bottom and top switches on a single-phase limb are in on state. The occurrence of the inverter shoot-through in the arm underpins the SBI theory of operation. These characteristics are not available in standard inverters, making them more suitable for power applications. As a result, the employment of SBI improves the overall reliability of the system. Furthermore, for power applications, this converter employs a PWM control approach [5-7]. However, when the system operates in different scenarios with parameter variation, this technique may loss its steady-state stability. Unfortunately, SBI has some limitations,
such as the value of the inverter duty ratio being limited from 0-0.5. After this value, the DC output voltages will tend to infinity and produce an unstable DC output voltage. As a result of this flaw, the DC link output voltage could not be increased to a certain DC output voltage. As a result of this flaw, the DC voltages will tend to infinity and produce an unstable limited from 0-0.5. After this value, the DC output such as the value of the inverter duty ratio being then, new mechanisms are designed to simulate gorillas' collective is formulated mathematically; The GTO algorithm is a novel metaheuristic [23] to optimize this complex and complex problem. The results demonstrated that the GTO performs better than comparative algorithms on most benchmark functions, particularly on high-dimensional problems, and it can provide superior results compared with other metaheuristics. So, this paper uses both the GTO (Particle Swarm Optimization) and PSO methodology. In this investigation, they were applied to optimize the tuning of the PID control mechanism to reduce the voltage fluctuations and enhance the output of the system. In this paper, a closed-loop control strategy is used to provide the GTO based optimal PID controller for the islanded modified DC nanogrid, decentralized operation of DG units and their local loads. The new application of the GTO algorithm is to optimally design the fixed gains of the PID controller. It is considered the key contribution of this research work. The controller is employed as the closed-loop control of the DG switched boost inverter. The suggested controller also allows the DG units to run efficiently despite the nanogrid load and topological fluctuation and uncertainty. The proposed control approach is used to control the DC and AC output voltages of the modified DC nanogrid system. The optimization procedure is based on a simulation-based optimization technique in which the goal function is built within the simulation program's model. As a result, establishing an objective function using other methods does not require a significant amount of effort or time. The criterion of integral squared error (ISE) is chosen as an objective function in the suggested approach, which expresses in the squared error signals of the inner loop. Five different cases are proposed and simulated to test the robustness of the controller with a comparison of the real-time (RT) test results using the OP-4510 RT-emulator. This paper is organized as follows. Section 2 presents the modified DC nanogrid system with the proposed controller. Section 3 shows the GTO model and its problem formulation. In Sections 4 and 5, the simulation results and implementation of the system test findings are reported. Finally, a conclusion is stated in Section 6.

2. The Modified DC-Nanogrid

Figure 1 depicts the proposed DC modified-nanogrid schematic diagram. It consists of a photovoltaic (PV)
renewable energy source as a generating power source, a single stage switched-boost inverter with a closed-loop control technique for power flow reliability.

As a generating power source, the redesigned DC nanogrid is mostly on photovoltaic (PV) renewable energy sources. It is one of the most cost-effective and efficient ways to deal with the energy crisis. It is also a clean, environmentally friendly, and naturally replenished energy source [24]-[25]. The PV module employed in this study is an IS4000P-300 watt module, which can be found in Appendix A. In addition, to optimize the operation of PV, a maximum power point tracking technology (MPPT) is necessary. This method ensures that the photovoltaic array system maintains its maximum power output regardless of temperature or irradiance variations. The Perturb and Observe (P&O) MPPT is tracked by continuously altering the duty cycle of the converter circuit's power electronic switches to fulfill MPPT operation [26]. A single-input multi-output switched boost inverter (SBI) links the source with the average load demand in the modified DC nanogrid system. SBI is a single-stage power converter capable of simultaneously supplying DC and AC loads from a single DC input voltage source. It can generate a higher or lower AC output voltage than the DC supply value. Furthermore, it has superior EMI noise immunity in comparison to the standard two-stage power converter nanogrid, reducing the risk of a fault occurring.

Fig. 1: Schematic diagram of the modified DC nanogrid

Fig. 2: Optimal Closed-loop control for the DC link voltage of SBI for the modified nanogrid
As a generating power source, the redesigned DC nanogrid is mostly on photovoltaic (PV) renewable energy sources. It is one of the most cost-effective and efficient ways to deal with the energy crisis. It is also a clean, environmentally friendly, and naturally replenished energy source [24]-[25]. The PV module employed in this study is an IS4000P-300 watt module, which can be found in Appendix A. In addition, to optimize the operation of PV, a maximum power point tracking technology (MPPT) is necessary. This method ensures that the photovoltaic array system maintains its maximum power output regardless of temperature or irradiance variations. The Perturb and Observe (P&O) MPPT is tracked by continuously altering the duty cycle of the converter circuit’s power electronic switches to fulfill MPPT operation [26]. A single-input multi-output switched boost inverter (SBI) links the source with the average load demand in the modified DC nanogrid system. SBI is a single-stage power converter capable of simultaneously supplying DC and AC loads from a single DC input voltage source. It can generate a higher or lower AC output voltage and AC loads from a single DC input voltage source. A low-pass L-C filter is also connected across the inverter bridge’s output to minimize its harmonic content [6]. The inverter modes of operation depend mainly on both intervals non-shoot-through state and shoot-through state. The classic sinusoidal PWM with voltage switching level was used to build the SBI control signals. This technique is demonstrated in detail in [27, 28] during positive and negative half cycles of the sinusoidal modulation signal Vm(t).

2.1. The Proposed Control Strategy

2.1.1. PWM control technique

The control signal for switches (S1, S2) GS1, GS2 is generated by comparing the reference modulation signal Vm(t) with a high frequency (f1) triangular carrier wave Vtri(t) of amplitude Vp during the first half cycle of the sine wave (Vm(t) > 0). The carrier wave must be adjusted so that (f1 >> f0), resulting in an approximately continuous sinusoidal reference wave at Vref(t). The gating control signals for the remaining three switches (GS1, GS2, and GS) are obtained by combining the triangle Vtri(t) with two constant DC voltages Vst, -Vst, to generate ST1 and ST2, respectively. By the same way, the negative – half cycle control signal for the switches are produced.

The standard PWM method should be updated to be able to be used in the SBI’s shoot-through condition. The improved approach has been shown and described in detail in [29] - [30]. Similar studies can be found in [31].

2.1.2 Model reference closed-loop DC-link voltage control

The DC-modified nanogrids are connected with each other via a DC link to contain the open energy system. So, the closed-loop control technique will keep the DC-link voltage of the grid constant or equal to the reference value under any disturbance. As a result, the AC output voltage will also remain constant. The control signal that achieves this process is the DC voltage level (Vdc) which directly effects on triggering the switch (S). The relations between the output DC voltage (Vdc, Vac, D, and the controlled signal voltage (Vst)) are determined according to the following equations [17],[30]:

\[ D = 1 - \frac{V_{st}}{V_p} \]  \hspace{1cm} (1)

\[ V_{st} = \frac{2 \times V_{ac}}{2 \times V_{dc} - V_B} \]  \hspace{1cm} (2)

\[ V_{dc} = \frac{M}{V_{ac}} \]  \hspace{1cm} (3)

Then, the AC-output voltage of SBI can be given as:

\[ V_{ac} = M \times V_{dc} = M \times (1 - D/1 - 2D) \times V_B \]  \hspace{1cm} (4)

Where, M is the modulation index of SBI and Vp is the peak value of the triangular wave and equal to 2. The robustness of the proposed controller is achieved by proposing a reference model for the actual DC-link voltage signal that deduces its block diagram from the above relations (Eqs. 1 and 2) – as shown in figure 2. Furthermore, this control technique uses a PID controller with a small tolerance value to adjust the output DC voltage and the DC reference voltage as shown in figure 2. In this technique, the actual output DC voltage (Vdc) is compared with the reference value (Vdc). And then the proposed PID controller is used to adapt the controlling signal voltage (Vst) and the duty ratio (D) according to the error signal. The classical design of the PID controller is used - for the first time- according to the Ziegler-Nichols formula. According to this design, the main gains of the controller parameters are Kp, Ki, Kd such that Kp = 5 \times 10^{-7}, Ki = 5 \times 10^{-7}, Kd = 1 \times 10^{-6}. Also the system has a very small value of an offset tolerance to compensate for the DC output voltage and minimize the error. As a result, the output voltage will remain also constant according to the relation between the DC and AC output voltages [29].
3. Problem Formulation

The main parameters of the PID controller obtained by using classical method are not optimum and lead to increase in error signal. Depending on the system may be unstable and may operate with a lot of oscillation and a huge overshot. Therefore, optimizing the PID control gains of its parameters is the main target of this work.

3.1 Objective function

In this study, the error produced from the difference between the actual and the reference DC output voltages is optimally controlled. Equation 5 presented the controlled error that must be integrated by the Gorilla troop optimization technique.

\[ e = V_d^a - V_{dc} \]  

The main target of this optimized problem is minimization of the error to achieve the intended goal, taking into account the operational constraints. The optimization process is done for the PID controller of the SBI DC link output voltage. The GTO code is built using the MATLAB environment. Multiple runs are carried out to achieve the best fitness value in each individual run; the proposed technique assigns a new set of optimal PID gains and the objective function value. The objective function can be described as follows:

\[ ISE = \int_0^T e^2 dt \]  

where ISE is the integral sum of errors. From the global runs, the lowest fitness value is finally extracted with the associated PID gains. The proposed range for all gains was selected according to the initial values obtained from the traditional method mentioned in the above section. The values ranges of the designed variables are:

\[ 1.3365 \times 10^{-7} \leq K_p \leq 4.0083 \times 10^{-7}, \]
\[ 3.1367 \times 10^{-7} \leq K_i \leq 9.4102 \times 10^{-7}, \]
\[ 3.6191 \times 10^{-7} \leq K_d \leq 1.0857 \times 10^{-6}. \]

It should be noted that the PID control parameters are limited with tiny variations. This occurred due to the high sensitivity of the SBI for the duty-ratio variation as mentioned above.

3.2 Gorilla Troops Optimization Algorithm (GTO)

The Optimiser of Gorilla Troops [32] is an optimization technique that is free of gradient and mimics the group behavior of gorillas. A troop of gorillas consists of a gorilla as an adult male, called a silverback, and gorillas as multiple adult females with their young. A silverback gorilla is over 12 years old and gets its name from the distinctive hair on his back during adolescence. Furthermore, the silverback is the troop leader, making all decisions, settling conflicts, guiding others to food resources, deciding group actions, and being in the care of safety. Male gorillas between the ages of 8 and 12 are known as black backs because they lack silver-colored back hair. They serve as the group's backup fighters and are linked with it. The male and female of gorillas generally move to a new group from the group in which they were born. Male gorillas, on the other hand, are more prone to break away from their original group and form their own army to attract females for migration. However, a few male gorillas, however, prefer to remain with the original troop and follow the silverback. In case of silverback death, males may engage in a vicious war for group supremacy and adult female mating. The precise mathematical model for the GTO algorithm is constructed on the previous concept of the behavior of a gorilla group in nature. GTO is an intelligent algorithm. It is divided into three sections: initialization, exploration, and exploitation. Each of them is explained in the following.

3.2.1. Phase 1: Initialization

In this phase, it was assumed that the D-dimensional space contains N gorillas. In space, the position of the i-th gorilla is as follows:

\[ X_i = (X_{i1}, X_{i2}, X_{iD}), i = 1, 2, \ldots, N \]  

As a result, the initiation for the populations of gorillas will be determined as follows:

\[ X = \text{rand} (N,D) (U_b L_b) + L_b \]  

where \( U_b \) and \( L_b \) indicate the upper and lower search range boundaries, while \( \text{rand} (N \text{ and D}) \) denotes the matrix with \( N \) rows and the values of \( D \) columns, and all elements are randomly selected between 1 and 0.

3.2.2. Phase 2: Exploration

Once gorillas leave their initial colony, they will go to a variety of natural locations, some of which they may or may not have seen before. All gorillas are considered candidate solutions in the GTO algorithm, and the silverback is the best solution in each optimization process. To correctly imitate such natural migration behavior, for the exploration stage, the gorilla position update equation was created using three alternative ways, including unknown migrating sites, migrating around familiar locations, and traveling to other groups, as illustrated in Equation 9.

\[ (U_b - L_b) \times r_2 + L_b, \quad r_1 < P \]
\[ (r_3 - C) \times X(t) + L \times X(t), \quad r_3 \geq 0.5 \]
\[ X(t) - L \times \left( L \times \left( X(t) - X_B(t) \right) \right), \quad r_4 \times \left( X(t) - X_B(t) \right), \quad r_1 < 0.5 \]
The time current iteration \( t \), \( X(t) \) is the current position of the individual gorilla vector, and the candidate location of search agents in the following iteration is \( GX(t + 1) \). Furthermore, \( r_1 \), \( r_2 \), \( r_3 \), and \( r_4 \) are all random numbers between 0 and 1. In the current population, \( X_A(t) \) and \( X_B(t) \) are two randomly picked gorilla places. \( P \) is a constant. The values are randomly generated in [C, C], and \( Z \) specifies a row vector in the problem dimension. In addition, the parameter \( C \) is determined using equation (10):

\[
C = ( \cos (2 \times r_5) + 1 ) \times (1 - \frac{1}{\text{Maxiter}}) \tag{10}
\]

where \( \cos (.) \) is the cosine function, \( r_5 \) is selected randomly between 0 and 1, and the maximum number of iterations is \( \text{Maxiter} \). In Eq. (11), the parameter \( L \) might be calculated as follows: Where \( l \) is a random selection between [1, -1],

\[
L = C \times l \tag{11}
\]

At the end of the fitness investigation, the values for every newly generated candidate \( GX(t + 1) \) solutions are evaluated. \( GX \) will be kept and replaced with the original solution \( X \) if it is better than \( X \), i.e., \( F(GX), F(X) \), where \( F(.) \) signifies the fitness function for a certain problem \( t \). Furthermore, the silverback \( X_{\text{silverback}} \) chosen as the best choice at this time.

### 3.2.3 Phase 3: Exploitation

While the other male gorillas are still young, the silverback is powerful and healthy when the troop is first created. They follow Silverback’s orders in pursuit of a variety of food sources and diligently serve the silverback gorilla. In the troop, younger black backs may get involved in a violent battle with the other males over mating with the adult females and the leadership, as the silverback grows old and eventually dies. There are two behaviors that have been highlighted for earlier models. These models are silverbacks that fight for adult female gorillas. The parameter \( W \) is inserted at the same time to govern the transition between them. If \( C \) is greater than \( W \) in Eq. (10), the silverback is chosen for the first technique. This can be computed as follows:

\[
GX(t + 1) = L \times M \times (X(t) - X_{\text{silverback}}) + X(t) \tag{12}
\]

where \( L \) is also evaluated using Eq. (11). \( X_{\text{silverback}} \) indicates the best solution obtained thus far, and \( X(t) \) denotes the current position vector. In addition, Eq. (13) can be used to derive the parameter \( M \):

\[
M = \left[ \left( \frac{1}{N} \sum_{i=1}^{N} X_i(t) \right) / N \right]^{\frac{1}{2}} \tag{13}
\]

\( X_i(t) \) specifies the current iteration position vector of the gorilla and \( N \) denotes the population size.

The latter mechanism is chosen if \( C < W \), and the location will be updated according to the relation:

\[
GX(t + 1) = X_{\text{silverback}} - (X_{\text{silverback}} \times Q - X(t) \times q) \times A \tag{14}
\]

\[
Q = 2 \times r_6 - 1 \tag{15}
\]

\[
A = \varphi \times E \tag{16}
\]

\[
E = \begin{cases} N_1, r_7 \geq 0.5 \\ N_2, r_7 < 0.5 \end{cases} \tag{17}
\]

\( X(t) \) signifies the current location in Eq. (14), and \( Q \) denotes the impact force, which is calculated using Eq. (15). In Eq. (15), \( r_6 \) is a random number between 0 and 1. Furthermore, Eq. (16) evaluates the coefficient \( A \) utilized to simulate the intensity of the competition violence, where signifies a constant, then the value of \( E \) is computed according to the equation. \( r_7 \) is similarly a random number in [0, 1] in Eq. (17). If \( r_7 \) is less than 0.5, \( E \) is a 1-by-D normal-distribution random-integers array, with \( D \) representing the spatial dimension. Instead, if \( r_7 \) is less than 0.5, \( E \) is a random number that follows the normal distribution. Similarly, the fitness values for the freshly generated candidate \( GX(t + 1) \) solution are determined at the end of the exploitation procedure. The \( GX \) solution will be kept and used in the upcoming optimization if \( F(GX), F(X) \). While the silverback \( X_{\text{silverback}} \) is the ideal solution for all people. The flow chart is shown in Fig. 3 for the GTO-algorithm.

### 4. Real-time Implementation of the Proposed System

Real-time emulation results for the proposed system are presented and compared with Matlab/Simulink simulation results through this section, proving the validity of the proposed scheme. The technology of the real-time digital simulation is very important for the electric system designing and testing to save money, time, and protect the real-physical system. Many test functionalities can be introduced with this technology. This technology is sophisticated in direct conversion of all Matlab/Simulink models to run in real time with the help of an additional software compilation [33].

So, in this paper, the OPAL RT-4510 is used as one of the more efficient real-time simulators in the market. The OPAL company introduced it as 2 in 1 platform. This means that it operates as a hardware-in-the-loop (HIL) and also a rapid control prototyping (RCP).
This digital simulator uses the RT-Lab software package as a compiler for the Matlab/ Simulink programs. Figure 4 shows the whole experimental rig. It implies the host computer with its console, OP4510 digital simulator, and OP8660 HIL-controller and data acquisition interface to provide supplementary signal conditioning [35]. The values of these output real-time analog signals are limited by the port maximum output voltage (i.e. 16V). Therefore, all signals are scaled according to their values. This scaling is done through the model of Matlab/ Simulink. In all cases, the waveforms for the reference and actual values of the DC voltage are scaled down by 100. In addition, the AC voltage is scaled down by 50. Furthermore, the grid voltage is scaled down by 20 [36]. However, the control signal and duty ratio are scaled down by 1.

5. Results and Discussion

The main aim of this section is to check the effectiveness and illustrate the performance of the suggested novel closed-loop control approach in preserving both the DC and AC output voltages at the expected level under different functioning conditions of the nanogrid. The proposed system was tested with GTO as an optimization algorithm and compared with PSO as another optimization. The optimization fitness function depends mainly on minimizing the controller error. To check the strength of the GTO, 30 iterations were applied for the controlled system. Several scenarios are realized to test the robustness of the proposed closed-loop control approach. Those scenarios comprise (i) a sudden increase in the SBI input voltage, (ii) a sudden decrease in the SBI input voltage, (iii) a sudden decrease in the DC reference voltage ($V_{dc}^*$), (iv) a sudden increase in the DC reference voltage ($V_{dc}^*$), and (v) a sudden change in the modulation index.

The final optimized values for the gains of the main parameters of the proposed GTO and PSO controllers are tabulated in Table 1. The Matlab/ Simulink simulation results are compared with real-time test results to check their suitability and applicability. The table implies all the main SBI-inverter data. Real-time experimental work is only implemented for the GTO algorithm.

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<td></td>
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Table 2: SBI parameter

<table>
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<td>switching frequency, $f_s$</td>
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<td>capacitor, $C$</td>
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<td>output filter capacitor, $C_f$</td>
<td>10 μF</td>
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<tr>
<td>AC and DC load, resistive</td>
<td>variable</td>
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</table>

5.1. Case 1:

In this scenario, the modified nanogrid is activated in an off-grid mode. It is initially operated with a PV-grid voltage $V_g=80$ V. The voltage is then increased stepwise to 106V at $t = 0.2$ seconds as illustrated in Fig. 5(a). The solid-blue line represents the GTO-algorithm and the dashed-yellow line represents the PSO-results. Figures 5 (b) and (c) show the controller signal voltages and the duty ratio responses, respectively. The controller action is able to track the signals even after the input suddenly changed, in order to keep the SBI Inverter outputs constant. Figures 5 (d) and (e) show the robustness of the closed-loop control signal to stabilize the DC and AC output voltages, respectively. The maximum overshot for GTO is less than that obtained with PSO. Furthermore, the dc-voltage control signal ($V_{st}$) is inversely proportional to the duty ratio (D) as shown in Figures 5 (b) and (c). The right figure represents the simulation, and the left one is the real-time for all figures.

5.2. Case 2:

This case studies the sudden decrease in the voltage as an input to the SBI ($V_g$) from 106 V to 80 V at the time $t = 0.2$S at constant DC and AC loads $R_{dc}=500 \, \Omega$, $R_{ac}=100 \, \Omega$ – shown in figure 6 (a). The response of the control signal ($V_{st}$) and duty-cycle ratio (D) are illustrated in Figure 6 (b and c). As shown, the GTO-algorithm contributes towards increasing the time response and also decreasing the overshoot for both signals. This fast response for the control signal and duty ratio will directly affect the response of the DC-link voltage and keep it constant around the setting value of the reference signal (i.e. 622V). This will lead to making the AC-output voltage of SBI also constant (i.e., 220V).

5.3. Case 3:

This case shows a sudden decrease in the reference voltage ($V_{ref}$) from 311 V to 622 V at step time $t=0.3$S) with the same DC and AC loads – as in case 1- ($R_{dc}=500 \, \Omega$, $R_{ac}=100 \, \Omega$) and constant input voltage ($V_g$) =112.8V as shown in figure 7(a). This case illustrates the direct effect of changing the reference voltage for the DC link of SBI. The control system responded to this change and, depending on both control signal and duty ratio, are changed to decrease the actual dc-link voltage of the inverter. The control signal is increased and the duty ratio is decreased, as shown in figures 7 (b and c). For both signals, the time response and overshoot are improved with GTO rather than PSO. The SBI-AC output voltage is directly affected by the DC-link voltage as described in Equation 4. The AC voltage equals M times the DC-link voltage. In this case, M=0.5, so the maximum value for the AC voltage is $V_{ac}=311 \, V$ (220 V rms value).

5.4. Case 4:

This case tests a sudden increase in the reference voltage ($V_{ref}$) from 622 V to 311 V at step time $t=0.3$S ($R_{dc}=500 \, \Omega$, $R_{ac}=100 \, \Omega$) and constant input voltage ($V_g$) =112.8V as shown in figure 8 (a). The real-time result will verify the control action for this case and will discuss in details in the next section. The control signal is decreased and the duty ratio is increased – as shown in Figures 8 (b and c). For both signals, the time response and overshoot are improved with GTO rather than PSO. This will contribute towards a rapid response to increase the DC-link actual voltage of SBI (as shown in Figure 8a). As described in case 3, the output AC voltage of the SBI will doubled (increased from 155.5 V to 311V maximum value, i.e., from 110V to 220V rms value).

5.5. Case 5:

This case represents a change in the modulation index by changing the ratio between the peak values of the reference and carrier waves at $t=0.3$S. The sudden change of the modulation index from 0.5 to 0.25 will lead to change in an AC output voltage according to equation 4. In addition, the reference voltage is kept constant at 622 V. Both DC and AC output voltages of the inverter will be affected by this disturbance, but the controller is
responded. So, the DC-voltage is kept constant, but the AC will be reduced to its half value (i.e. 110V rms).
(a) Step-increase in PV-grid voltage ($V_g$) (simulation and real time)

(b) Control-signal response ($V_{st}$) (simulation and real time)

(c) Duty cycle ratio ($D$) (simulation and real-time)

(d) DC link actual and reference signals ($V_{dc}$) (simulation and real time)

(e) AC-output voltage ($V_{ac}$) (simulation and real time)

Fig. 5: Case 1 (step increase of the PV grid voltage as input to SBI)
(a) Step-decrease in PV-grid voltage ($V_g$) (simulation and real time)

(b) Control-signal response ($V_{st}$) (simulation and real time)

(c) Duty cycle ratio ($D$) (simulation and real-time)

(d) DC link actual and reference signals ($V_{dc}$) (simulation and real time)

(e) AC-output voltage ($V_{ac}$) (simulation and real time)

Fig. 6: Case 2 (step decrease of PV-grid voltage as input to SBI)
(a) Step-decrease in DC-reference voltage ($V_{dc}^*$) (simulation and real time)

(b) Control-signal response ($V_{st}$) (simulation and real time)

(c) Duty cycle ratio ($D$) (simulation and real-time)

(d) AC-output voltage ($V_{ac}$) (simulation and real time)

Fig. 7: Case 3 (step decrease of the DC-link reference voltage of the SBI)
(a) Step-increase in DC-reference voltage ($V_{dc}^*$) (simulation and real time)

(b) Control-signal response ($V_{st}$) (simulation and real time)

(c) Duty cycle ratio ($D$) (simulation and real-time)

(d) AC-output voltage ($V_{ac}$) (simulation and real time)

Fig. 8: Case 4 (step increase in SBI-DC link reference voltage)
Fig. 9: Case 5 (step change of SBI-modulation index from 0.5 to 0.25)
6. Conclusions

This manuscript proposed a DC-link voltage controller for a single-input, multi-output SBI within an open energy system. This controller used a combination of model reference and PID-controller for fine tuning and improve the system time-response. The gains of the controller are optimized using GTO as a metaheuristic optimization problem and then compared with the PSO as another optimization algorithm. Five scenarios were studied to test the robustness of the controller against sudden change for PV-grid voltage, the reference voltage, and SBI-modulation index. The time response of the DC link was improved with GTO-algorithm and the overshoot became less than that obtained using PSO-algorithm for most cases. The system was implemented in real time with the help of OP4510v hardware in the loop and a rapid control prototyping platform. All RT signals are obtained via OP8660 HIL controller and data acquisition set. The simulation and real-time results are congruent and ensure the validity of the proposed system to be implemented as a real-time physical system.

Appendix A:

PV module specifications (IS4000PS)- 300 Wp at STC:

\[ P_{\text{max}} = 300 \text{W}, \quad P_{\text{PTC}} = 280 \text{W}, \quad P(I_{\text{max}}) = 7.98 \text{A}, \]
\[ V(I_{\text{max}}) = 37.6 \text{V}, \quad I_{\text{SC}} = 8.54 \text{ A}, \quad V_{\text{OC}} = 45 \text{ V}, \]
\[ C_{\text{eff}} = 17.4\%, \quad M_{\text{eff}} = 15.5\%. \]

References:


**Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)**

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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**Conflict of Interest**

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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