Parameter Optimization of Bidirectional Three-Phase DC-AC Power Inverter by an Improved Particle Swarm Optimization based Fractional Order PI Controller for the Grid Forming Operation

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Abstract- Nowadays, it is becoming more remarkable for bidirectional power conversion from battery energy sources. These structures can be used for three-phase loads and they also have a common application in Micro-grid systems. This paper is mainly focused on parameter optimization of the system by using improved particle swarm optimization (PSO) in grid forming operation of dual active bridge series resonant converter (DABSRC) topology, in term of total harmonic distortion (THD). Fractional order proportional integral (FOPI) controller is used to simulate DABSRC regarding to THD factor in this system. The results are also compared to genetic algorithm (GA) and conventional PSO. While all algorithms achieved the same optimum control parameters, a significant reduction of computation time has been reported by improved PSO in terms of THD.

Keywords: THD, Optimization, PSO, Fractional order control

1. Introduction

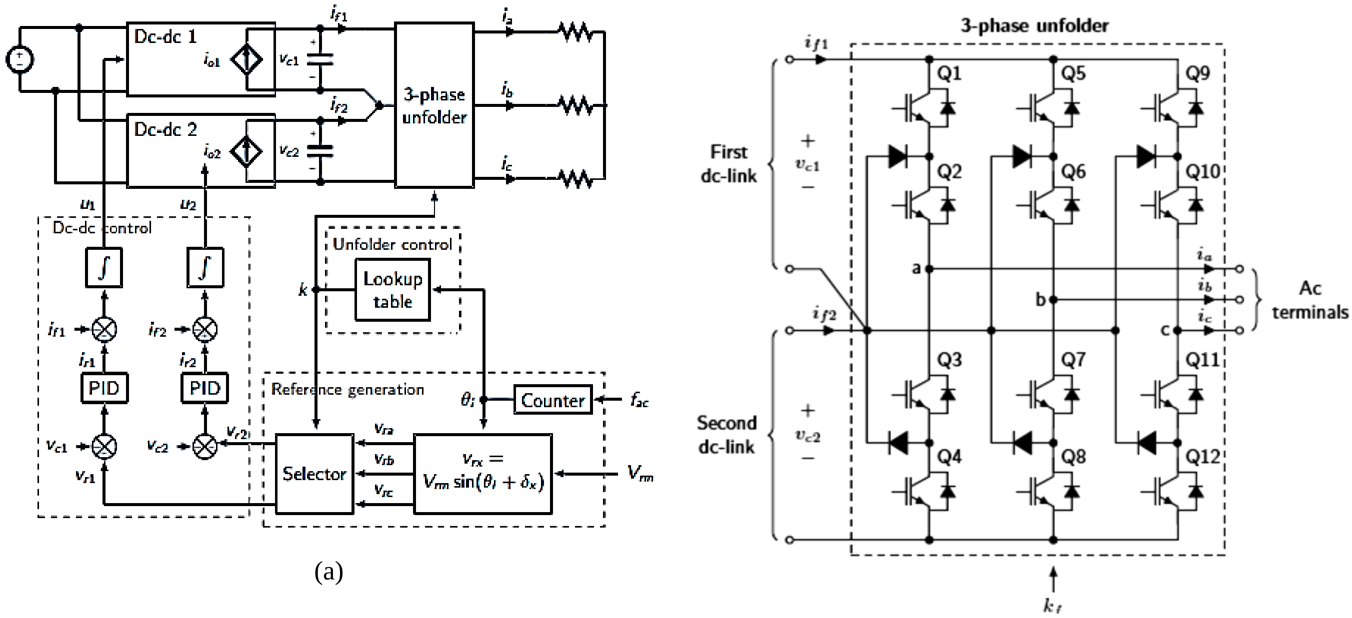
GA-based optimization and other optimization methods have been used extensively in inverter and DC / DC converter design. Emara et al., have compared the modified PSO algorithm with other known optimization techniques such as conventional PSO, line search and GA to find out the superior model that minimizes error of the currents for an induction machine between simulation and test system [1]. The simulation results show that the modified PSO is better than other optimization techniques in obtaining machine parameters that reduce errors occurring in the system. Kaviani et al., have presented some methods to overcome and minimize low voltage harmonics at the output of multilevel inverter by using PSO, continuous genetic algorithm (CGA) and sequential quadratic programming (SQP) [2]. The results show that PSO has better performance in terms of eliminating or minimizing harmonics in the multilevel inverter output compared to CGA and SQP. Modified species-based PSO algorithm has been used with adaptive adjustment of niche radius to apply a related problem that involves lots of switching angels [3]. To show the validity and effectiveness of the proposed technique, it was first proven in theory then successfully applied in real time to an eleven level cascaded H-bridge inverter. Shindo et al., have presented a single phase inverter design by using the PSO algorithm to perform effective switching [4]. Firstly, they have designed inverter in a simulation environment. Then, they confirmed the results of simulation via using an implementation circuit. The results show that the simulation result was consistent with the results of implementation circuit. Ganguly has proposed a PSO-based algorithm for compensation of reactive power in networks [5]. When it is optimistically apportioned, served in a desired good case, it can excellently minimize the power loss. Mohammadi and Akhavan, have used GA and PSO methods together for selective harmonic elimination problem to obtain the base voltage constant, for DC energy in the cascaded multilevel inverters [6]. The aim of the proposed methods is to determine the matching fire switching values of the inverter. The results show that PSO is better than GA in finding the proper and desired values that are needed for the inverter to operate in healthy condition. In another study, a different and unusual optimization technique is implemented by using PSO to find switch forms of CMOS inverter [7]. The proposed new method was compared with the real coded genetic algorithm (RCGA) and classical PSO. Results show that the PSO with constriction factor and inertia weight approach (PSO-CFIWA) has significant characteristics such as finding desired inverter parameters and has satisfactory switching angles to reduce harmonics. Baskin and Caglar, have introduced a PSO-based PID controller for permanent magnet synchronous motor (PMSM). To show the effectiveness and superiority of the proposed controller, the PID controller whose parameters were obtained by using the Ziegler Nichols method is also applied to the same system and the results obtained for both controllers were compared [8]. The results show that the PSO-based PID controller is the best choice for stabilizing the speed loop of PMSM.

In this paper, an improved particle swarm optimization based FOPI controller is used to optimize the THD of bidirectional three-phase DC-AC power inverter for grid forming operation of dual active bridge series resonant converter. In addition, in order to examine the performance of the proposed PSO, genetic algorithm and conventional PSO methods are also used to find the optimum parameters of the controller and the results obtained were compared.

2. Theoretical Approach of Dabsrc

As shown in Fig. 1, the topology includes three-phase expanding circuit that means unfolder to feed AC load by DC-side that contains two dual-active bridge series-resonant converters (SRC) circuits [9].

Both SRCs are controlled one by one to produce variable DC-link for the unfolding in DC/AC mode in the grid forming operation. These DC-link voltages are converted to AC by the unfolder. The operation will be reversed in AC/DC mode. PID controllers, reference generation, look up table and Unfolder are controlled by FPGA. Look up table is used to control switching sequences of the unfolder [10]. The advantages of this structure are removing PWM inverter and filter, decrement of the capacitance of DC-link, the optimization of THD by relating advances in control strategy of the SRCs [9]. Parallelization of the two DC-links with the AC circuits, it remodels or rectifies from the three-phase AC to conventional 60 degree segments of sinusoidal wave forms which exist at the variable DC-link nodes [11], [12]. More to clarify that, the capacitors of DC-link which placed among the unfolder and SRC do not stock network energy and are basically required by filtering of the output current of SRC.



(a)

(b)

Fig. 1. a) Block Diagram, b) Unfolder circuit of the system

3. Fractional Order PI Controller

The fractional-order integral-differential operator is represented by and defined as follow [13],

$$ {}_aD_t^r = \begin{cases} \dfrac{d^r}{dt^r} & r \rangle 0 \\ 1 & r = 0 \\ \displaystyle\int_a^t (dt)^{-r} & r \langle 0 \end{cases} \qquad (1) $$

where and are the upper and lower limits of operator a and t is the fractional order. Several mathematical definitions for this type of differentiation could be listed in the references but three of them is enough here, that are Caputo, Grünwald–Letnikov (GL) and the Riemann–Liouville (RL), are accepted. The mentioned definitions have its own properties and are given below. The definition of GL [14] is,

$$ {}_aD_t^r f(t) =_{h\to 0} \lim h^{-r} \sum_{j=0}^{\left[\frac{t-a}{h}\right]} (-1)^j \binom{r}{j} f(t-jh) \qquad (2) $$

Where $\left[\dfrac{t-a}{h}\right]$ is the integer part. On the other hand, for $n-1\langle r\langle n$ the RL definition can be defined as,

$$ {}_aD_t^r f(t) = \frac{1}{\Gamma(n-r)} \frac{d^n}{dt^n} \int_a^t \frac{f(\tau)}{(t-\tau)^{r-n+1}} d\tau \qquad (3) $$

where $\Gamma(.)$ is the gamma function. Finally, for $n-1\langle r\langle n$ the Caputo method can be written as [15,16].

$$ {}_aD_t^r f(t) = \frac{1}{\Gamma(n-r)} \int_a^t \frac{f^n(\tau)}{(t-\tau)^{r-n+1}} d\tau \qquad (4) $$

In this paper, Caputo definition is used due to extensively been used in engineering application. FOPID controller is generally donated by $PI^{\lambda}D^{\mu}$ and the equation below shows the transfer function,

$$ G_c(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \qquad (5) $$

Here λ and μ are real positive numbers. P, I and D defines proportional gain, integration and differentiation of constant K respectively. Determination of these parameters makes a significant improvement on PID. Therefore, several optimization methods are proposed to find the optimum value for the FOPID controller parameters. In this paper, we used PSO for the determination of the controller parameters.

3.1 Tuning of The FOPI Controller by PSO

3.1.1 Improved PSO

The improvement flowchart which basically focuses on handling of the population (particles) has presented in Fig. 2. The weighted selection method is used to decrease the swarm size population. Reducing the swarm size by half will undoubtedly reduce CPU time in terms of optimization issue.

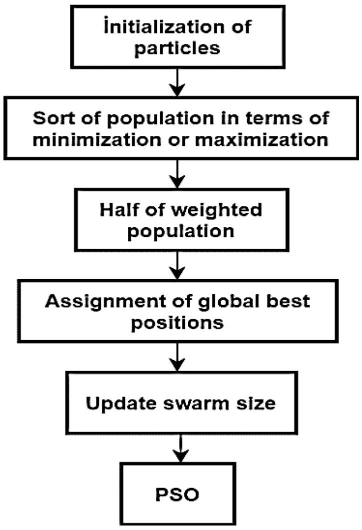


Fig. 2. Flowchart of improved PSO

Simulation results of revised PSO and conventional PSO are compared in Table 1. The simulations are tested for thousand times for the same initial conditions. The improve PSO was first simulated on traditional test functions as shown in Table 1. A brief information about these functions; first function is De Jong 1 function which is simple to apply, shows a stable and convex form. While two methods achieved the optimum value of the De Jong 1 function, a significant decreasement of CPU time has been retrieved (58 %). Second function De Jong 2 which is a typical function used in optimization testing, and also known as a “banana function”. Score point is located at a deep figurative valley; difficult to get the minima considering this shape, that’s why it is used for tests. Similarly, about 40 % gain is marked as in De Jong1. De Jong 3 has a feature of incoherent, uniform modal, separativity and extensitivity. Optimum value of the De Jong 3 function is related with the variable number. A reduction of 20 % was achieved for three variables but 48 % for ten, that’s great for advanced PSO. The fourth is De Jong 4 function which has a Gaussian noise. 45 % ratio is indicative for three variables and 20 % for more variables. The other name of De Jong 5 is called Shekel’s function, furthermore a_{ij} and ci are some constants which can be found in literature. This function differs with separability with local maxima associated with the a_{ij} matrix. Superior results and excellent performance (62 %) for three variables, unfortunately 10 % for ten. Our last function is Rastrigin function which is presented by customizing De Jong 1 with a cosine factor.

Table 1. Calorific Values (CV) for Palm Fruit Shell Briquettes

Test Functions	Number of Variables	Mathematical Expression	PSO		Improved PSO		Reduction in CPU time (%)
			Iterations	CPU time (s)	Iterations	CPU time (s)	
DeJong1	3	$f(x)=\sum_{i=1}^{n} x_i^2$	80.1	35.99	59.308	15.23	**58**
	10		168.8	75.64	128.4	31.52	**58**
DeJong2	3	$f(x)=\sum_{i=1}^{n-1} 100(x_{i+1}-x_i^2)^2+(1-x_i)^2$	62.248	9.138	45.6	5.71	**38**
	10		123.4	28.6	113.2	16.652	**42**
DeJong3	3	$f(x)=\sum_{i=1}^{n} \mathrm{int}(x_i)$	116.4	35.44	79.42	28.28	**20**
	10		107.25	106	98.25	55.25	**48**
DeJong4	3	$f(x)=\sum_{i=1}^{n} i x_i^4 + Gauss(0,1)$	19011	8276	488.6	4512	**45**
	10		21237.6	10411.6	548.4	8452	**19**
DeJong5	3	$f(x)=\sum_{i=1}^{m} \frac{1}{\sum_{j=1}^{4}(x_j-a_{ij})^2+c_i}$	63.4	89.12	43.688	33.78	**62**
	10		111.92	511.25	200.9	461.75	**10**
Rastrigin	3	$f(x)=10n+\sum_{i=1}^{n}(x_i^2-10\cos(2\pi x_i))$	112.12	133.5	114.125	79.7	**40**
	10		178.3	605.83	170	294.4	**51**

3.1.2 Improved PSO

Simply application, lower variables and high convergence are basic assets of this algorithm. As an alternative of the structures require long CPU times, PSO appears. Thus, this algorithm is preferred in this complex system and also compared with GA. Improved PSO shows better CPU time results with better optimization as it is referred above. The boundaries of the algorithm are presented in the Table 2.

PSO optimization results based FOPI control, advanced PSO and GA are displayed in Table 3 for 2 kVA RL load. Why it is displayed for one load, because the others reach also about the same time scales reasonably. Focusing on the Table 4 one can see each algorithm carried out the optimum value, but it took enormously distant CPU cycles. The table shows GA need more CPU time drastically. Another convincing improvement is the reduction in CPU times as predicted: 42 % lower CPU time. PSO should be selected for complex systems in terms of simulation time as it is seen in this Table. On the other hand, simulation was run for different load types for testing as it is shown in the Table 4.

Table 2. Parameter Boundaries for PSO and GA

Parameters	Lower	Upper
K_p	0.01	0.03
K_I	50	180
K_D	0.1	0.2
λ	0.4	0.9
μ	0.3	0.8

Table 3. Comparison of Simulation Times of the Algorithms for the load of RL (2 kVA).

Algorithm	K_p	K_i	λ	K_D	μ	THD	CPU time
PSO	0.0255	52	0.477	0.22	0.663	1.65 %	62 h
Improved PSO							36 h
GA							144 h

It could be seen that FOPI dominates PI ones in some loads. More inductive loads cause more corruption in THD values as expected.

Table 4. Comparison of PI and FOPI in terms of THD Values

Load	PI	FOPI	
Resistive (100 Ω)	0.44	1.34	THD (%)
RL (2.5 kVA)	3.49	2.9	
RL (2 kVA)	2.45	1.65	
RL (1 kVA)	0.95	0.98	
IM (1.5 kW)	0.92	5.6	

Also inductive loads have some glitches in Voltage characteristic as seen in the Fig. 3. Since the system is optimized for worst conditions with different loads, the resistive load has higher THD value than 1 kVA load. The system was tested up to 2.5 kVA load because of saturation limits. On the other hand, the Induction Machine (IM) load result of PI controlled algorithm achieved impressively higher performance over FOPI one. But however FOPI can get the same result with different control parameters that require dynamic parameter tuning for FOPI.

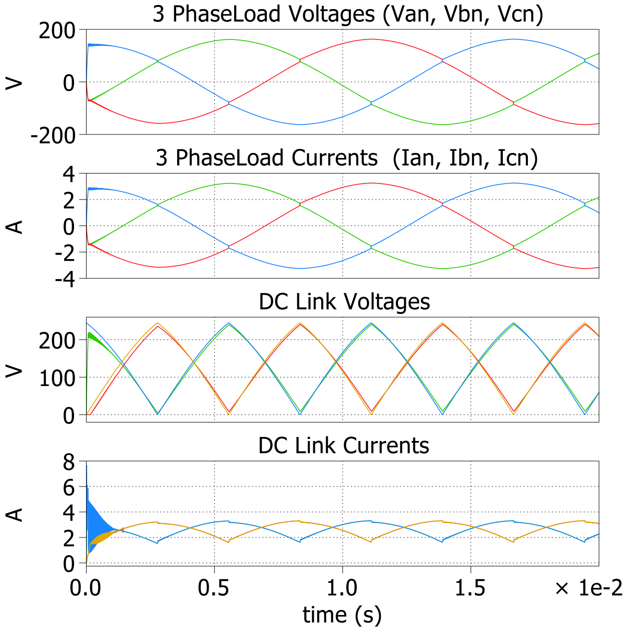


Fig. 3. Illustration of Simulation results for 2 kVA load optimized by Improved PSO.

4. Conclusions

In this paper, the THD Optimization of a FOPI controlled Bidirectional Three-Phase DC-AC Power Conversion in Grid Forming Operation is presented by an improved PSO. The main goal of this design is to minimize switching complexity of conventional inverter and to obtain pure sinusoidal wave form without harmonic elimination methods. In the first stage, the comparison between PI and FOPI expose the superiority of fractional controller over PI except IM load. However, FOPI can get the same result with different control parameters, dynamic tuning of parameters is mandatory. In the second stage, significant reduction in CPU time proves that the new approach makes the algorithm more optimistic. Dominating the CPU time for GA presents that PSO is an alternative solution for optimization of sophisticated architectures which need hard CPU time. The future work will be the FPGA implementation of FOPI controller and verification of optimum in hardware. Another future work will be multi variable optimization in terms of efficiency and different loads. Also online optimization methods can be implemented because of nonlinearities. A dynamic FOPID / PID control should exactly give the best results for this system. The full paper will include better optimized simulation results, dynamic load response of the system for the proposed optimization algorithm, objective function and comprehensive introduction.

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