Optimization of SMC parameters Using GA in a Full-Bridge Dc-Dc Converter

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Abstract— Converters are one of the inseparable parts of Distributed Generation systems. They are variety of control methods implemented in converters in order to control their output quantities. One the robust methods which is considerably useful in such applications is Sliding Mode Control which is robust against inherent uncertainties and imprecisions of converters. The proposed method is explained and formulated using state space average model of a sample full-bridge converter in order to have a perfect current tracking of a full-bridge converter. Since the best output is obtained using the optimum design parameters, the parameters of the full-bridge converter are optimized using Genetic Algorithm (GA) in order to have the best response.

Keywords- Sliding Mode control, Genetic Algorithm, Full Bridge Converter, Current Tracking, Parameter Optimization

I. INTRODUCTION

Clean Power Generation (CPG) is at the center of the attention these days because it can protect environment from the problems of classical power generation such as greenhouse gas emission and pollution. Besides environmental repercussions, energy demand rise and depletion of energy resources are other reasons of CPG appearance [1-3]. There are different types of environmental-friendly generations systems such as wind turbines, hydro turbines, photovoltaic arrays, biomass and fuel cells. Advances in energy storage devices have greatly assisted the flourishing penetration of distributed generation (DG) into installation and operation of power generation plants [4-6].

Most of the DG generators do not have a considerable and well-regulated DC output. To tackle this problem, a dc-dc power electronic converter is used in order to regulate and boost the output to the desired value [7]. Power converters can be assigned to perform some functions such as output regulation under load variation or source change [1]. Several types of converters have been studied for such purpose. Buck converter, Boost Converter, Buck-Boost Converter, Push-Pull boost convert and full bridge converter are the most common converters which are used in DG applications [8-14]. To have the best performance of a converter, several control methods have been used [15-21]. The reason of this implementation is the generation systems limitations rooted in their physical characteristics. In order to have an acceptable control over the output of the DG system (DG) there are two ways exists. First, Control the rate of the physical and chemical quantities which take part in reactions to produce electricity. For example, output voltage of a fuel-cell is made of the reactions between hydrogen and oxygen. Thus if the rate of the Hydrogen and Oxygen is controlled, the output value is controllable [22]. Since controlling Chemical and physical quantities are not easy, a second way which is the control implementation in the connected converter is used. It is possible to regulate and change the output of a converter by changing its duty cycle [2].

PID controllers are the most common use controller in the case of converter control. They can improve system transient response during load step changes and source changes [23, 24] or using loop up tables instead of multiplier in order to minimize the energy consumption [25]. PID controllers are valid only around the nominal power point of the system and they cannot have an acceptable response in large scale disturbances and wide variety of load changes. Intelligent modern controllers such as fuzzy controller are alternatives controllers to obtain better performance of converters [8, 18] . They are robust against such disturbances and uncertainties. In [26], PID method and fuzzy logic theorem are combined via a Linear Quadratic Regulator (LQR) to have a better performance. Some other combinations of fuzzy logic and PID are presented in [27, 28]. Besides Fuzzy and PID controllers, the most appropriate controller in order to use in converter control applications is nonlinear control methods. These controllers are the best options because of uncertainties in converters rooted in their elements and design. In addition to uncertainties, the behavior of controllers is nonlinear and the best option to use in their application is a nonlinear controller.
to be valid in a large variety of values. This Basis is derived from the non-minimum phase nature of converters, variability in their structure and unpredictable nonlinear load changes [29, 30]. Sliding mode control is one of the well-fitted and useful methods converter studies especially in DG connected samples. [31] presents a simple unified approach to the design of fixed-frequency pulse width-modulation-based sliding-mode controllers for dc-dc converters operating in the continuous conduction mode. The problem of combining interleaved operation of several identical power converters with a hysteretic control is solved in [32] by inducing a sliding regime to all inductor currents in a ring configuration. In some references a combination of sliding mode with other methods is presented [11, 28, 33-36]. The sliding mode fuzzy controller combines the advantages of both fuzzy controllers and sliding mode controllers. It also has advantages of its own that are well suited for digital control design and implementation [28]. In [37-39], investigations on Buck, Boost and Buck-Boost converters are carried out using SMCs in order to reach a desired voltage profile tracking during a load change, start-ups and transients. Full Bridge buck converter is studied in a part of the [40] in comparison with a cascaded connection boost converter for voltage, but not considering the transformer.

In this paper, a proposed sliding mode controller (SMC) is introduced and implemented in a full-bridge converter using its average model. The parameters of SMC are optimized using GA to have a proper response from two points of view: settling time and final value. The proposed method is confirmed using simulation in tracking performance and settling time.

II. FULL BRIDGE CONVERTER AND THE CONTROL SYSTEM

A. Full-Bridge Converter Performance and Average Modeling

Fig.1 depicts the general schematic of a full-bridge converter circuit.

Reference source not found.

Fig.1. The full-bridge converter

The sample full bridge converter is made of a full bridge power converter (Q1 to Q4), a high turns-ratio transformer with ratio 1: n, a diode bridge rectifier and an output filter. The switches (Q1 to Q4) are located diagonally and turned on and off. The pulses are sent to the switches using a PWM pulse generator with the time duration of DT. The PWM pulse generator has the value D as duty cycle input. The transformer eases boosting the output voltage. The average model is beneficial for simulation because of not using multiple switches and other electrical elements. Therefore, the time of simulation decreases. Also the state space model is suitable for controller design and stability analysis.

B. Implementation of Sliding Mode Controller in a Full Bridge Converter

There are two stages exist in the design of a SMC controller; first, determining the sliding surface to provide sliding condition and second, reaching the sliding surface. Consider the following single input dynamics.

\[ x^{(n)} = f(x) + b(x)u(t) \] (6)

\[ f(x) \] and \( b(x) \) both are not exactly known but the former is upper bounded by a known continuous function of \( x \) named \( F \) where \( |f - \hat{f}| \leq F \) and the latter sign is known and it is also upper bounded by a continuous function of \( x \). The objective is determination of \( u \).

The tracking error vector is defined by the following equation:

\[ \hat{x} = x - x_d = [\hat{x}_1 \; \hat{x}_2 \; \ldots \; \hat{x}_n] \] (7)

\[ s(x; t) = (d + \lambda)^{n-1} \hat{x} \] (8)

Where \( \lambda > 0 \) and \( n > 0 \) are design parameter and system order respectively.

It is obvious that if the tracking error equals zero then (8) equals zero. It means:

\[ x = x - x_d = 0 \iff s(x; t) = 0 \] (9)

Where \( x_d \) is the desired output value.

Therefore, it is possible to keep \( s \) at zero with a proper choice of \( u(t) \) at (1).

A control law is introduced in order to keep the \( s \) at zero.

\[ \frac{1}{2} \frac{d}{dt} s^2 \leq -\eta \|s\|^2 \] (10)

where \( \eta > 0 \) is a design parameter.

State-space equations of the full-bridge converter can be obtained from (1)-(5) as

\[ x_i = \frac{-R_s 2d - r_i (1 - 2d)}{L} x_i - \frac{1}{L} x_2 + \frac{2dn}{L} V \] (11)
\[
\dot{x}_2 = \frac{1}{c} x_1 - \frac{1}{RC} x_2
\]
\[
V_0 = x_2
\]

By changing (11) and (12) in the form of (6) we have:
\[
\dot{x}_1 = -\frac{r_d}{L} x_1 - \frac{1}{L} x_2 + \left(2 \left(\frac{r_d - R_m}{L}\right)x_1 + \frac{2n}{L} V_d\right)\]
\[
\dot{x}_2 = \frac{1}{c} x_1 - \frac{1}{RC} x_2
\]

\(d\) is the controlling parameter of the system is the same as \(u\) in (6). Since there is no \(d\) available at (14) only the tracking of \(x_1\) is accessible. Of course, it is highly likely that the tracking \(x_1\) leads to the stability of \(x_2\). Hence,
\[
\hat{f}_1(x) = -\frac{R_d}{L} x_1 - \frac{1}{L} x_2
\]
\[
\hat{b}_1(x) = \left(2 \left(\frac{r_d - R_m}{L}\right)x_1 + \frac{2n}{L} V_d\right)
\]

\(\hat{f}\) is an estimation for \(f\) because of some available uncertainties in full-bridge converter. Another reason for this estimation is the semiconductor nonlinear characteristic. This explanation is also correct for \(b\) and \(\hat{b}\).

Considering \(n = 2\) in (8), the sliding surface is as follows
\[
s = \ddot{x} + \lambda \dddot{x}
\]

The general form of (12) in comparison with (6) can be written as
\[
s' = f(x) + b(x)u(t)
\]

Where \(f(x)\) and \(b(x)\) can be the function of \(x_1\) and \(x_2\).

By replacing (20) in (19) we have
\[
s' = f' + bu - \dot{x}_d + \lambda \ddot{x}
\]

Now the effort is on the finding of the appropriate \(u\) in order to make \(s = 0\).

by taking the estimations on \(f\) and \(b\) into account, the best \(u\) is found to satisfy \(s = 0\)

Firstly by considering \(b = 1\), the following equation is derived
\[
\dot{u} = -\hat{f} + \dot{x}_d - \lambda \ddot{x}
\]

The above conditions in (21) and (22) are formulated with the assumption of \(s = 0\), but there are some uncertainties in the parameters and the problem is out of the \(s\) plane. Therefore, \(u\) should be defined as
\[
u = \dot{u} - k \text{sgn}(s)
\]

Where \(\text{sgn}(s) = \begin{cases} 1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \\ 0 & \text{if } s = 0 \end{cases}\)

Secondly, \(u\) is derived from (23) while \(b \neq 1\)
\[
u = b^{-1} (\dot{u} - k \text{sgn}(s))
\]

By putting (24) in (20) and after some simplifications, the sliding surface could be achieved as
\[
s = f - bb^{-1} \hat{f} + bb^{-1} \dot{x}_d - bb^{-1} \lambda \dddot{x} - bb^{-1} k \text{sgn}(s) - \dot{x}_d + \lambda \ddot{x}
\]

In order to calculate \(k\), \(s = 0\) must be solved, hence
\[
b^{-1} k \text{sgn}(s) = (f - bb^{-1} \hat{f}) + (1 - bb^{-1})(-\dot{x}_d + \lambda \ddot{x})
\]

Where \(\hat{b} = \left(\frac{b_{\text{max}}}{b_{\text{min}}}\right)^{0.5}\)

After some simplifications with regard to \(f = \hat{f} + (f - \hat{f})\) \(k\) is represented as
\[
k \geq \beta(F + \eta) + (\beta - 1)\left|\hat{b}\right|
\]

Where
\[
\beta = \left(\frac{b_{\text{max}}}{b_{\text{min}}}\right)^{0.5} \quad \text{and} \quad 0 < b_{\text{min}} \leq b \leq b_{\text{max}}
\]

After calculation of \(k\), \(x\) is capable of tracking \(x_d\) and it can be controlled.

There are three design parameters. \(F\) is assumed as the radius of error between \(f\) and \(\hat{f}\). Thus it is predicted that lower \(F\) results in better tracking accuracy and lowering the error. \(\lambda\) is another SMC parameter. \(\lambda\) is the coefficient of the non-derivative term of the sliding surface presented in (8). It affects the resolution of tracking the desired point in comparison with the reaching speed. Moreover it may influence the amount of the chattering. \(\eta\) is a positive constant design parameter and defines the sliding condition. It also implies that some of the system uncertainties and disturbances can be tolerated while still keeping the surface invariant set. Also, \(\eta\) can be influential on system dynamic especially in the system speed and changing in the proportion of chattering. General scheme of the proposed control system and its output and input is shown in Fig.2.

**Fig.2. General Scheme of the Proposed SMC**

### III. OPTIMIZATION OF THE PROPOSED SMC USING GENETIC ALGORITHM

In this paper, GA is used in order to optimize the three mentioned parameters of the proposed SMC to have the best output. In order to start the solution, first population size should be determined at the first step. This population is obtained from accidental quantization of chromosomes. These numbers are inserted to the function which is going to be optimized. The next step is injecting the generated population to objective function. The aim of this action is creating of fitness function which is derived from chromosomes. In this case proper answers are kept and others will be omitted. This circle will be continued until the size of population is reached.
the following chart illustrates the proposed GA.

![Fig.3. The proposed Genetic Algorithm chart](image)

IV. IMPLEMENTATION OF THE PROPOSED METHOD

In order to verify the proposed method MATLAB/SIMULINK is used. The Converter model is modeled as follows:

![Fig.4. The Model of Dc-Dc Full-bridge Converter in MATLAB/SIMULINK](image)

As it can be seen in above picture, because of some simulation problems such as increasing the time of the simulation and increasing the error message of the software during simulation with electrical parameters the full-bridge converter is simulated using block diagrams instead of resistors and capacitors.

As it can be understood from the simulated SMC, the inputs of the SMC are $x_1$ and $x_2$. The output of the system is the appropriate duty cycle which is sent to the converter switches.

For implementation of GA, MATLAB/GA toolbox is used.

The specification of the 5 kW sample Full-Bridge converter is presented in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>$V_i$</td>
<td>50 V</td>
</tr>
<tr>
<td>Inductance</td>
<td>$L$</td>
<td>7 mH</td>
</tr>
<tr>
<td>Capacitance</td>
<td>$C$</td>
<td>330 μH</td>
</tr>
<tr>
<td>Diodes Resistance</td>
<td>$R_d$</td>
<td>1 mΩ</td>
</tr>
<tr>
<td>Switches On-Resistance</td>
<td>$R_s$</td>
<td>5 mΩ</td>
</tr>
<tr>
<td>Transformer Ratio</td>
<td>$n$</td>
<td>100</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>$f_s$</td>
<td>2000 Hz</td>
</tr>
<tr>
<td>Load Resistance</td>
<td>$R_L$</td>
<td>12.5 Ω</td>
</tr>
<tr>
<td>Equivalent Thevenin Resistance</td>
<td>$R_{th}$</td>
<td>100.002 Ω</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS AND DISCUSSION

In this part, the simulations and results using MATLAB/SIMULINK and MATLAB/GA toolbox is given and the appropriate explanations are also presented.

A. Design Parameter Study

First of all to have a better recognition of the design parameters their approximate effect on the tracking performance is discussed.

1) Effect of $F$

$F$ may decrease the resolution of tracking. For example, $F=10$ expresses that the absolute deviation of the available values of the converter elements from original values are less than 10. The default values of other SMC parameters are as follows:

$$
\begin{align*}
\eta &= 1 \\
\lambda &= 10
\end{align*}
$$

The optional value for $x_1$ to track is 22.5 A. The simulated waveforms for $F=0.1, F=10, F=100$, and $F=1000$ are shown in

![Fig.5.](image)

2) Effect of “$\lambda$”

The simulation is performed for different values of $\lambda$ using the following values for other parameters of the SMC:

$$
\begin{align*}
F &= 0.1 \\
\eta &= 1
\end{align*}
$$

Also, in this study, the desired value of current is equal to 22.5 A.
Inductor Current By Changing The Lambda Value

As it can be understood from the above figure, by increasing \( \lambda \), the slope of the current rises and the system reaches the steady-state condition in a shorter time.

Also it has got a significant effect on the tracking accuracy. For example the tracking error for \( F=10 \) is 0.0049%.

3) Effect of “\( \eta \)”

To study the effect of \( \eta \), the default values for other parameters are

\[
\begin{align*}
F &= 0.1 \\
\lambda &= 10
\end{align*}
\]

The relative tracking error is around 4% for \( \eta = 1000 \), around 0.44% for \( \eta = 100 \) and approximately zero for other values.

B. Simulation of SMC Parameter Optimization Using GA

The estimated parameters to start simulation are:

\[
\begin{align*}
F &= 0.1 \\
\eta &= 1 \\
\lambda &= 100
\end{align*}
\]

And the result is presented in Fig.8. with a green dotted line.

Now the effort is to optimize the mentioned values in order to have the best response using GA. The simulation is run for the following values:

\[
\begin{align*}
\text{Variable Names} &= F, \eta, \lambda \\
\text{Population size} &= 10 \\
\text{Generation} &= 50 \\
\text{Absolute error} &= 0.001
\end{align*}
\]

The optimized values for converter parameters are as follows:

\[
\begin{align*}
F &= 0.051607 \\
\eta &= 0.39232 \\
\lambda &= 778.27
\end{align*}
\]

And the specified point that the output has reached the best value is 14. It means that in 14 ms, the answer has got the best characteristics with the mentioned optimized values.

Now the effort is to run simulation for different values for absolute error to have a better understanding of the optimized points. The values for absolute error are 0.1, 0.01, 0.001 and 0.0001.

As it can be seen in Table II, the decrease in absolute error leads to the increase in reaching time.

<table>
<thead>
<tr>
<th>Absolute Error</th>
<th>0.1</th>
<th>0.01</th>
<th>0.001</th>
<th>0.0001</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F )</td>
<td>0.086175</td>
<td>0.038527</td>
<td>0.051607</td>
<td>0.37661</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.607</td>
<td>1.1747</td>
<td>0.39232</td>
<td>0.15359</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>812.69</td>
<td>645.24</td>
<td>778.27</td>
<td>701.02</td>
</tr>
<tr>
<td>Reaching Time (ms)</td>
<td>8</td>
<td>13</td>
<td>14</td>
<td>19</td>
</tr>
</tbody>
</table>

The following figure depicts the inductor current simulated wave form for different values of absolute error.

As it can be seen, the settling time is different for different values of absolute error. This method can be helpful during much sensitive cases like connection of a DC-DC converter to a distributed generator such as fuel cell and photovoltaic.
VI. CONCLUSION

Since most of the distributed generators does not have a considerable and regulated output, converters are implemented in DG systems in order to overcome the mentioned problems. Full-bridge converter is a useful converter which can perform both output regulation process and output boosting. SMC is a robust method which can be employed in order to force the variables of the converter to track a reference value. SMC has three design parameters. To obtain the best performance of the converter and controller these parameters should be optimized. In this paper GA is used in order to optimize the SMC parameters in order to have the best current output with the best tracking performance.

REFERENCES