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Control Strategy Based on Associative Memory Networks for a Grid-Side Converter in On-Grid Renewable Generation Systems Under Generalized Unbalanced Grid Voltage Conditions

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Abstract – *This paper presents a control strategy based on Associative Memory Networks (AMN) for controlling a grid-side converter in the On-grid renewable generation systems under generalized unbalanced grid voltage conditions. In the proposed scheme, the controller operates in a rotating synchronous reference frame, where standard PI controllers are utilized in the fast inner dual current loops to track the current references, while in the outer loop, the AMN is used as a nonlinear adaptive integrator combined with a simple proportional controller for the DC link voltage regulation. By using the simulation study, it is shown that the overshoot of the proposed control system in transient state is lower compared with that of the optimal PI controller. Consequently the overvoltage of the DC link capacitor due to abrupt changes of the active power generated by renewable generation systems under both balanced and unbalanced grid voltage conditions could be effectively avoided.*

***Keywords**: Associative Memory Networks, Generalized Unbalanced Grid Voltage Conditions, Grid Side Converter, On-Grid Renewable Generation Systems*

Nomenclature

$e_{\alpha\beta s}$, $v_{\alpha\beta s}$	Grid and converter voltage vectors
$i_{\alpha\beta s}$	Grid current vector
L	Line inductance
R	Line resistance
C	DC link capacitance
ω_g	Grid frequency
ω_s	Synchronous frequency
V_{dc}	DC link voltage
e_{dq}, i_{dq}	Rotating grid voltage and current vector
e_d, i_d	d-axis component of grid voltage and current vector
e_q, i_q	q-axis component of grid voltage and current vector
u_b	AMN output
P_0, Q_0	Constant active and reactive power
P_1, P_2	Active power high-order coefficients
Q_1, Q_2	Reactive power high-order coefficients
$\sigma(.)$, X	AMN basis function output and input vector
w, p	AMN weight and the weight numbers
u_{pi}	Output of PI controller
s	Laplace operator
K_p, T_i	Proportional gain and Time integrator of the PI controller
T_{cl}	Time constant of the closed loop system.
$V(.)$	Lyapunov function candidate
e	Error of the closed loop control system
$i_{dc\ s}$	Renewable power source DC current
$i_{dc\ g}$	Grid side converter DC current

Superscripts

j	Imaginary number
$+$	Positive sequence
$-$	Negative sequence

I. Introduction

Due to the rapid development of the distributed and green power generation systems, the utilization of Grid Side Converters (GSCs) in recent years has increased significantly. In many cases, the main role of a GSC in the On-grid green generation systems is to channel the real power generated by the renewable power sources to a three phase grid system. However in some cases such as DFIG based wind turbine systems [1] and the On-grid renewable power generation systems combined with DC microgrids [2], the GSC should also have the capability to drain the power from the grid. Besides being utilized as a bridge between the green power sources and the grid, nowadays GSC is often used as AC/DC rectifier systems [3]-[5], flexible AC transmission systems [6], active power filters and VSC transmissions [7][8].

From a control system point of view, one of the several problems faced by control system designers is the grid voltage unbalances which are frequently found especially in weak grid systems such as at remote and rural areas where the distributed green power generation systems are usually installed. In practice, the main causes contributing to the unbalanced grid conditions are the unbalanced distributions of single phase and the non-

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linear loads [9]. An unbalanced grid voltage condition could be also caused by several conditions, such as a nonsymmetrical transformer winding, open wye, and open delta [10]. The conventional controllers of the GSC will operate properly under balanced grid voltage but not under unbalanced voltage conditions. It is well-known that the operation of the conventional controllers under unbalanced voltage conditions will inject a second harmonic both in the DC link voltage and in the injected power, and they also will turn up the odd harmonics of the grid current [11]. This is due to the standard controllers that generally just take care of the positive sequence voltage disregarding the appearance of the negative sequence of the voltage. To reduce the bad influences of the unbalanced voltage conditions, the GSC controller practically should take care both of the positive and negative sequence components of the grid voltage. In this case, the controller should have the capability to inject (or drain) both the positive and the negative sequence components of the three phase-grid current. There are several approaches found in the literature to overcome the adverse domino effect of the unbalanced voltage conditions. All of them are extended variants or modifications of the existing standard GSC controllers. In a rotating synchronous reference frame control strategies, Rioual et al. [12] compensated the unbalanced voltage conditions by controlling both the positive and negative-sequence current components just in the positive synchronous reference frame (SRF), whereas Song and Nam [13] used a strategy, well-known as a dual current control system in which the positive and negative sequence components of current are regulated by the conventional Proportional Integral (PI) controllers in the positive and negative synchronous reference frame independently. To enhance the steady state performance of the dual current control system, Bo Yin et.al [14] used a technique called output power control method in which the commands of the inner current loop are computed and determined so that the input power references are distributed appropriately. Whereas the transient performance improvement of the dual current control system by employing a hybrid control technique in which resonant gains are combined with PI controller was proposed by Suh and Lipo [15]. Like Bo Yin et.al, Suh and Lipo also tried smoothing the fluctuation of the power and the DC link capacitor voltage by modifying a current reference at the inner loop of the control system.

The extended version of stationary reference frame control system of the GSC under unbalanced grid voltage conditions has been proposed in literature [16]-[19].

Besides the rotating and stationary reference frame control systems, several extended version of the direct power control (DPC) under unbalanced voltage conditions can be found in literature. Garcia, et.al [20] tried to reduce the distortion of three phase currents under unbalanced voltage conditions by directly controlling the power so that symmetrical sinusoidal grid current would be obtained. In [21], Shang, et.al presented an improved sliding mode controller-based DPC for dealing with the unbalanced voltage conditions.

All the GSC control strategies operating under generalized unbalanced voltage conditions basically have their own pros and cons. For example, although a good dynamic transient response could be obtained by the DPC strategy, this control strategy will create more harmonics compared with the PI controller.

But on the other hand, compared to the DPC strategy, in the transient state, the PI-based vector control generally will trigger an excessive overshoot mainly in response to sudden changes of the active power generated by renewable generation systems.

The phenomenon of sudden changes in power flow is commonly found in wind turbine-based power generation systems [24], [25] and in on-grid renewable power generation systems combined with DC microgrid.

This work proposes a control strategy based on B-Spline networks-typed AMN combined with a simple proportional controller for controlling the GSC under balanced and unbalanced voltage conditions. In the proposed scheme, the AMN is used as a nonlinear adaptive integrator placed in the outer control loop of the GSC. Whereas in the inner loop, a dual current control loop is adopted to control both the positive and negative sequence components of current. The proposed control scheme basically is the improvement of authors previous works [22], [23]. In these previous works, the designed AMN controller would give satisfactory performance to operate just under balanced grid voltage condition.

The purpose of this study is twofold: first, in the steady state, to reduce the DC link capacitor voltage and grid power fluctuations due to unbalanced grid voltage conditions. Second, in the transient state, to dampen overshoot of the DC link capacitor voltage due to sudden changes of the active power generated by renewable generation systems so that the overvoltage of the DC link capacitor could be avoided.

To show the effectiveness of the proposed AMN control system, in this paper, the performance of the designed controller is compared with that of a standard PI controller with symetrical optimum parameters [26].

By using Simulink software, it is shown that the proposed controller at initial condition could reduce the overshoot 15% lower than that of the PI controller in the response to disturbances. Even, since the AMN internally possesses the adaptive and associative properties, the improvement in the transient performance will be achieved if the relatively similar disturbance reoccurs in the control system. In these cases, the proposed controller is able to reduce the overshoot by almost 60% lower than that of the optimal PI control system both in the balanced and unbalanced grid voltage conditions.

II. System Model

II.1. GSC Model and Power Transfer Under Unbalanced Voltage Conditions

The main task of the GSC in grid-connected renewable power generation systems is to pass the electrical power generated by green power sources to the grid. Fig. 1 shows a general circuit configuration of the renewable power sources connected to a three phase grid via two converters that are controlled independently: the AC/DC or the DC/DC renewable energy source side converter (RSC) and the bidirectional DC/AC Grid Side Converter.

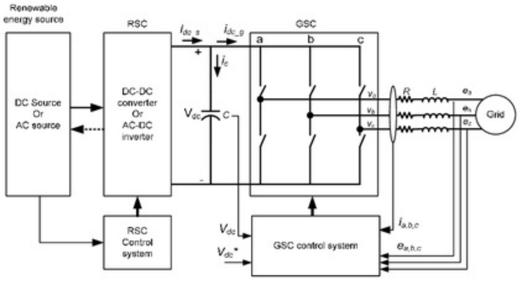


Fig. 1. Grid Side Converter in the on grid Renewable generation system

In many cases, the control objective of the RSC is to maximize the power generated by the green power sources (for instance by MPPT algorithm) in addition to convert an AC voltage or to boost a DC input voltage of the green power source to a certain DC-link voltage level, whereas the main task of the GSC is to inject the surplus energy at the DC link capacitor by means of the DC link voltage regulation. Because the main focus of this research is the control design of the GSC, this section will present the mathematical models related with the GSC system. In the stationary reference frame, the voltage relation of the GSC in Fig. 1 is given by:

$$v_{\alpha\beta s} = Ri_{\alpha\beta s} + L\frac{di_{\alpha\beta s}}{dt} + e_{\alpha\beta s} \qquad (1)$$

The grid voltage-$e_{\alpha\beta s}$ and the grid current-$i_{\alpha\beta s}$ under unbalanced voltage conditions mathematically could be represented:

$$e_{\alpha\beta s} = e_{dq}^{+}e^{j\omega_g t} + e_{dq}^{-}e^{-j\omega_g t} \qquad (2)$$

$$i_{\alpha\beta s} = i_{dq}^{+}e^{j\omega_g t} + i_{dq}^{-}e^{-j\omega_g t} \qquad (3)$$

where $e_{dq}^{+}e^{j\omega_g t}$ and $i_{dq}^{+}e^{j\omega_g t}$ are respectively the positive sequence of the voltage and current vector which rotate counterclockwise, whereas $e_{dq}^{-}e^{-j\omega_g t}$ and $i_{dq}^{-}e^{-j\omega_g t}$ are respectively the negative sequences of the voltage and of the current vector which rotate clockwise.

By substituting (2) and (3) to (1), and by assuming that the inverter could also have the capability to generate positive and negative sequence components of the voltage, then the dynamic model of the converter current in the rotating synchronous reference frame after simplification steps could be written:

$$\frac{di_d^{+}}{dt} = -\frac{R}{L}i_d^{+} + \frac{1}{L}v_d^{+} + \frac{1}{L}d_1 \qquad (4)$$

$$\frac{di_q^{+}}{dt} = -\frac{R}{L}i_q^{+} + \frac{1}{L}v_q^{+} + \frac{1}{L}d_2 \qquad (5)$$

$$\frac{di_d^{-}}{dt} = -\frac{R}{L}i_d^{-} + \frac{1}{L}v_d^{-} + \frac{1}{L}d_3 \qquad (6)$$

$$\frac{di_q^{-}}{dt} = -\frac{R}{L}i_q^{-} + \frac{1}{L}v_q^{-} + \frac{1}{L}d_4 \qquad (7)$$

where d_1, d_2, d_3, and d_4 are the terms related to the coupling effect:

$$d_1 = \left(-e_d^{+} + \omega_s L i_q^{+}\right) \qquad (8)$$

$$d_2 = \left(-e_q^{+} - \omega_s L i_d^{+}\right) \qquad (9)$$

$$d_3 = \left(-e_d^{-} - \omega_s L i_q^{-}\right) \qquad (10)$$

$$d_4 = \left(-e_q^{-} + \omega_s L i_d^{-}\right) \qquad (11)$$

For the generalized unbalanced grid voltage conditions, the grid power and the DC link voltage pratically will oscillate twice respect to the grid frequency. By referring to [27], the relation between the grid voltage and current components to the grid power could be represented:

$$P = P_0 + P_1 cos\left(2\omega_s t\right) + P_2 sin\left(2\omega_s t\right) \qquad (12)$$

$$Q = Q_0 + Q_1 cos\left(2\omega_s t\right) + Q_2 sin\left(2\omega_s t\right) \qquad (13)$$

$$\begin{bmatrix} P_0 \\ Q_0 \\ P_1 \\ P_2 \\ Q_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} e_d^{+} & e_q^{+} & e_d^{-} & e_q^{-} \\ e_q^{+} & -e_d^{+} & e_q^{-} & -e_d^{-} \\ e_d^{-} & e_q^{-} & e_d^{+} & e_q^{+} \\ e_q^{-} & -e_d^{-} & -e_q^{+} & e_d^{+} \\ e_q^{-} & -e_q^{-} & e_q^{+} & -e_d^{+} \\ -e_d^{-} & -e_q^{-} & e_d^{+} & e_q^{+} \end{bmatrix} \begin{bmatrix} i_d^{+} \\ i_q^{+} \\ i_d^{-} \\ i_q^{-} \end{bmatrix} \qquad (14)$$

Since the objective of this work is to inject just the constant active power (P_0) by manipulating the positive and negative sequence components of the current, then the appropriate reference for the current component should be found out. By inverting (14) and nulling the other power coefficients, the relation of the active power reference to the current component references could be represented as shown in (15) below:

$$\begin{bmatrix} i_d^{+*} \\ i_q^{+*} \\ i_d^{-*} \\ i_q^{-*} \end{bmatrix} = \frac{2P_0^*}{3D} \begin{bmatrix} e_d^+ \\ e_q^+ \\ -e_d^- \\ -e_q^- \end{bmatrix} \tag{15}$$

where:

$$D = \left(\left(e_d^+\right)^2 + \left(e_q^+\right)^2 \right) - \left(\left(e_d^-\right)^2 + \left(e_q^-\right)^2 \right)$$

II.2. The AMN Model

Due to several superiority and desirable features, such as a low cost computation and a local generalization property, the AMN is appropriate to be realized as an adaptive and on line controller for real time applications. Fig. 2 shows the block diagram that depicts the input-output data flow of the AMN.

Differently by other popular neural networks (for example Multi Layer Perceptron), for a certain input vector, not all the basis function will be activated, infact in this case, the AMN will just activate a small number of the basis functions. By referring to the block diagram of Fig. 2, the input-output relationship of the AMN mathematically could be represented as shown in (16):

$$u_b = \sum_{i=1}^{p} \sigma_i\left(X\right) w_i = \sigma^T\left(X\right) W \tag{16}$$

where X, $\sigma(.)$ and w are the input vector, output of basis function and adaptive weights respectively.

Due to the efficiency in computations, in this work, the B-Spline function is chosen as the basis functions in the input layer of the AMN. For the scalar input (x), the higher order of univariate basis functions output could be computed from the lower ones recursively as shown in (17) [28]:

$$\sigma_k^j\left(x\right) = \left(\frac{x - \lambda_{j-1}}{\lambda_{j-1} - \lambda_{j-k}} \right) \sigma_{k-1}^{j-1}\left(x\right) + \left(\frac{\lambda_j - x}{\lambda_j - \lambda_{j-k+1}} \right) \sigma_{k-1}^{j}\left(x\right) \tag{17a}$$

$$\sigma_1^j\left(x\right) = \begin{cases} 1, & \lambda_{j-1} \le x < \lambda_j \\ 0, & \text{others} \end{cases} \tag{17b}$$

where λ_j is knot of j-th basis function, $I_j = (\lambda_{j-1}, \lambda_j)$ is j-th interval, whereas k is the basis function order.

In the case of multivariate basis functions, the output of the AMN could be computed simply by dot product of the each univariate basis function output. The relation (18) below shows the output of the bivariate B-spline basis function used in this work:

$$\sigma\left(m,n\right) = \sigma_m\left(x_1\right)\sigma_n\left(x_2\right) \tag{18}$$

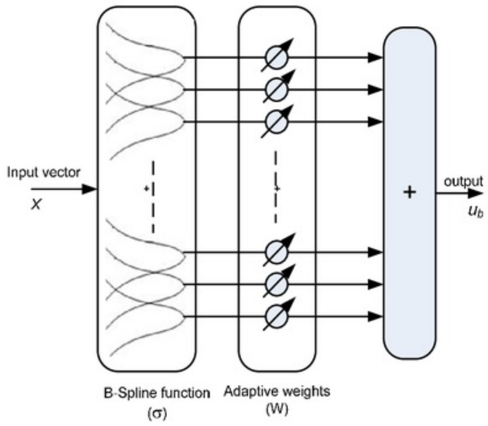


Fig. 2. Block diagram of the AMN

III. GSC Control Design

As already discussed shortly in Section II, the major task of a GSC control system is to inject the active power from the DC link capacitor to the grid.

By referring to (14), it could be seen that the active power which is injected to the grid is determined directly by the grid current component. So in this case, the four dynamic models of the current component (Eq. (4) until Eq. (7)) need to be controlled independently.

For each current dynamic model, the reference could be computed from (15). However as shown in (15), to compute the current component references, the appropriate active power reference (Po^*) should be obtained first.

By referring to the topology of the On-grid power generation system at Fig. 1, the reference of the active power (Po^*) practically could be obtained from the control output of the DC link voltage, because the active power which is injected to the grid is basically correlated with the DC link capacitor voltage: The DC link capacitor voltage will increase if there is power flow from the renewable power generation system.

III.1. Control Design of The Grid Current Dynamic

The main task of the inner current control system is to track the current references generated by (15). There are four linear dynamic models of the current component that need to be controlled independently:

$$\frac{di_n}{dt} = -\frac{R}{L} i_n + \frac{1}{L} v_n + \frac{1}{L} d_n, \quad n = 1,2,3,4 \tag{19}$$

where $i_1 = i_d^+$, $i_2 = i_q^+$, $i_3 = i_d^-$, $i_4 = i_q^-$, $v_1 = v_d^+$, $v_2 = v_q^+$, $v_3 = v_d^-$, $v_4 = v_q^-$, and d_1, d_2, d_3, and d_4 are the terms related to coupling effect and grid voltage (Eq. (8) until Eq. (11)) that could be regarded as disturbances.

By using a simple PI controller plus a feedfoward control, the controller output for each current component (v_n) could be represented by (20):

$$v_n = u_{PI\_n} - d_n, \quad n = 1,2,3,4 \tag{20}$$

where $u_{PI\text{-}n}$ is the PI controller output. By substituting (20) to (19), the dynamic of the current (19) could be represented by the transfer function form:

$$H(s) = \frac{I(s)}{U_{PI\_n}(s)} = \frac{1/R}{(L/R)s+1} \tag{21}$$

By considering that the Laplace transform of the PI controller is:

$$U_{PI\_n}(s) = K_P\left(1+\frac{1}{T_i s}\right)\left[I^*(s)-I(s)\right] \tag{22}$$

Then by substituting (22) to (21) and doing few simplication steps, the transfer function of the inner current control loop could now be represented by:

$$\begin{aligned} H(s) &= \frac{I(s)}{I^*(s)} = \\ &= \frac{(1/R)K_P(s+1/T_i)}{((L/R)s+1)+(1/R)K_P(s+1/T_i)} \end{aligned} \tag{23}$$

By selecting the following:

$$K_P = L/T_{cl} \tag{24}$$

$$T_i = L/R \tag{25}$$

then the final transfer function of the closed loop system of the each current component could be represented by:

$$H(s) = \frac{I(s)}{I^*(s)} = \frac{1}{T_{cl}s+1} \tag{26}$$

where T_{cl} is the desired time constant of the closed loop system. Fig. 3 shows the complete PI control block diagram of the current control loop for each sequence component.

III.2. Control Design of The DC Link Voltage

The DC link voltage control system have the responsibility to regulate the voltage of the DC link capacitor voltage at a certain reference such that the power generated by the renewable sources could be injected to grid automatically. By referring to Fig. 1, the DC link voltage dynamic could be written:

$$V_{DC} = \frac{1}{C}\int\left(i_{dc\_s} - i_{dc\_g}\right)dt \tag{27}$$

where i_{dc_s} and i_{dc_g} are respectively the renewable source DC current and inverter DC current injected to the grid via the GSC. By considering that the DC link power is equal to the grid active power:

$$V_{dc} i_{dc\_g} = P_0 \tag{28}$$

Then the DC link capacitor voltage dynamic could be written as a nonlinear differential equation as shown in (29):

$$\frac{V_{dc}}{dt} = -\frac{1}{C}\frac{P_0}{V_{dc}} + \frac{1}{C} i_{dc\_s} \tag{29}$$

Since the output active power has been previously controlled by controlling the sequence components of current (section III.1), and on the other hand, the current control dynamic is very fast compared to the dynamic of the DC link voltage, then for the AMN design process simplicity, the power control loop dynamic practically could be neglected, so the representation of the DC link voltage dynamic could be represented by (30):

$$\frac{V_{dc}}{dt} = -\frac{1}{C}u + \frac{1}{C} i_{dc\_s} \tag{30}$$

where $u = P^*/V_{DC}$ is basically the controller output which is the combination of the proportional gain controller and the AMN output:

$$u = K_p e + \sigma^T W \tag{31}$$

where e is the capacitor voltage error:

$$e = V_{dc} - V_{dc}^* \tag{32}$$

By substituting (31) and (32) to (30) and by considering the voltage reference as a constant, then the error dynamic of the DC link voltage control system could be found as shown in (33):

$$\dot{e} = -\frac{1}{C}K_p e - \frac{1}{C}\left(\sigma^T W - \frac{1}{K_p C} i_{dc\_s}\right) \tag{33}$$

From (33) it is shown that the error dynamic will be stable only if the AMN weights are updated such that in the steady state the second term of the right side of the relation is equal to zero.

In this work, the updating rules of the AMN weights are carried out by using the direct Lyapunov stability method as follow: Let choose a candidate of the Lyapunov function as represented at (34):

$$V(e,W) = e^2 + \left(\sigma^T W - \frac{1}{K_p C} i_{dc\_s}\right)^2 \tag{34}$$

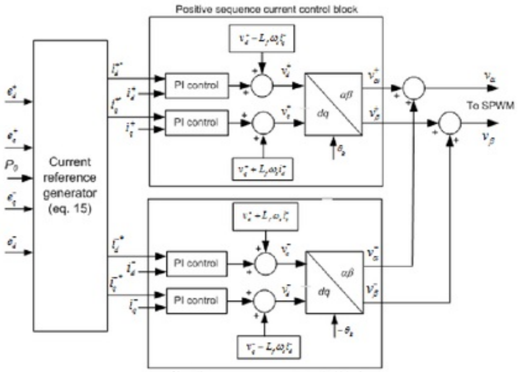


Fig. 3. Block Diagram of the inner current control loop

The time derivative of the above function is:

$$\dot{V}(e,W) = 2e\dot{e} + 2\left(\sigma^T W - \frac{1}{K_p C} i_{dc\_s}\right)\sigma^T \dot{W} \tag{35}$$

by substituting (33) to (35), it will be obtained:

$$\begin{aligned}\dot{V}(e,W) = -\frac{1}{C}2K_p e^2 - \frac{1}{C}2\left(\sigma^T W - i_{dc\_s}\right)e + \\ +2\left(\sigma^T W - i_{dc\_s}\right)\sigma^T \dot{W}\end{aligned} \tag{36}$$

if the term of $\sigma^T \dot{W}$ is chosen such that :

$$\sigma^T \dot{W} = \frac{1}{C} e$$

Then the time derivative of the weights could be found:

$$\dot{W} = \frac{\alpha e}{\sigma^T \sigma} \frac{1}{C}[\sigma] \tag{37}$$

so the chosen Lyapunov time-derivative is a negative definite scalar function as shown in (38):

$$\dot{V}(e,W) = -\frac{1}{C} 2K_p e^2 \tag{38}$$

In other words, by referring to (38) then the weights updating rule of (37) will be stable.

Because the outer DC voltage to be controlled is basically a regulator system, then in this work the appropriate inputs for the AMN to be chosen are the DC link voltage and DC link current. Fig. 4 shows the simulated DC link voltage control system block diagram.

To extract the grid phase information and the grid voltage and current sequence components, the Double-dicouple Second Order Integrator method (D-SOGI) – Frequency Lock Lopp (FLL) algorithm [29] is utilized.

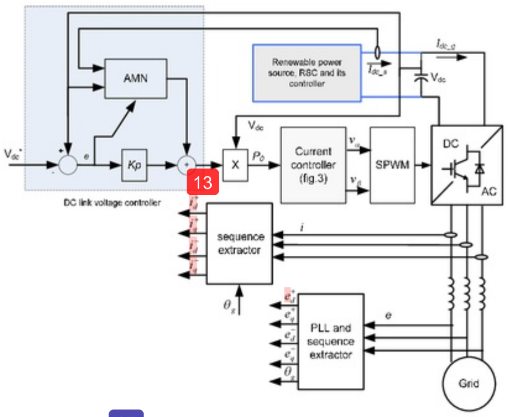


Fig. 4. DC link voltage control system block Diagram

To test the transient performance of the designed GSC control system in response to sudden power changes of the renewable power generation, in this work, the renewable power generation system block in Fig. 4 is emulated by the controlled AC power source.

IV. Simulation Result and Discussion

The performance of the proposed controller has been verified by the simulation study. The whole system model is run under Matlab-Simulink Power System Blockset environment. The Grid and GSC model parameters are depicted in Table I.

TABLE I
THE PARAMETERS OF THE GSC AND THE GRID

Plant Parameter	Value
R – Filter (ohm)	0.02
L – Filter (H)	0.01
C – Filter (uF)	1200
DC Link Voltage reference (volt)	650
Balanced grid voltage (rms)	380,380,380
Unbalanced grid voltage (rms)	250,380,380
frequency of the Grid (Hz)	50
frequency of the SPWM (kHz)	10
Time sampling (s)	0.0001

TABLE II
PI CONTROLLER PARAMETERS FOR THE INNER LOOP AND THE OUTER LOOP (FOR COMPARISON PURPOSES)

	Closed Loop	Method
The inner Loop	$\frac{1}{T_{cl}s+1}$	Pole Placement K_p=10, T_i=0.5
The outer loop	$\frac{1+a^2T_{cl}s}{1+a^2T_{cl}s+a^3T_{cl}^2s^2+a^3T_{cl}^3s^3}$	Symmetric Optimum: $a = 3$, $K_p = 0.4$ $T_i = 0.009$

TABLE III
PARAMETERS OF THE BSNN CONTROL SYSTEM FOR THE OUTER LOOP

AMN control Parameter	Value
Basis function (B-Spline) order	3
Number of the B-Spline function	12
Proportional gain	0.4
Adaptive gain – α/C	0.0023

For comparison purposes, in this work, the PI-based single current loop and PI-based dual current loop control system are simulated.

The optimal parameters for the inner current loops are obtained by utilizing the pole placement method as previously discussed in Section III.1. The inner loop time sampling and the closed loop time constant for the simulation model are 0.0001 and 0.001 s, respectively.

Whereas for the outer control loop, the optimal parameters of the PI controller are obtained by using a Symmetric Optimum technique. To damp the transient responses, the chosen symmetrical distance- *a* is 3.

The optimal parameters of the PI controller is calculated by using these methods are shown in Table II and the parameters of the AMN control system are shown in Table III.

IV.1. Simulation Result under Balanced Voltage Condition

In this subsection, the capability and the performance of the three diferrent control strategies in regulation under balanced voltage condition will be shown.

To investigate the transient performance of the proposed controllers, the GSC system is tested by a step change of the input power generated by the green power source emulator. Fig. 5(a) and Fig. 5(b) show respectively the step change of the DC current and the associated power injected to DC link via the green source converter system. For the DC current change in Figs. 5, the response of the DC link capacitor voltage and the grid power under the three different control schemes are shown in Figs. 6. Fig. 6(a) shows that in the transient state, the performance of the AMN control system with dual current control loop is more superior compared to that of the standar PI-based controllers.

In this case, the overshoot of the DC link capacitor voltage due to the sudden change of the source DC current under the AMN controller is more damped than that of the PI-based controllers. It is also shown that the DC link voltage responses under the PI-single and PI-dual current control loop are relatively the same; this is because both the controllers have the capability to control the positive sequence converter current.

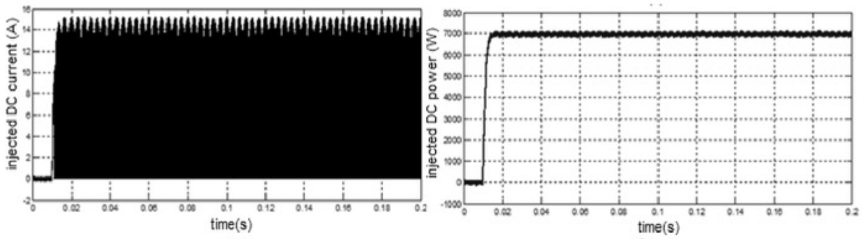
For the sudden change of the source DC current, the active power injected to the grid is shown in Fig. 6(b).

From the plots, it is clear that the AMN controller has a faster transient response compared to that of the PI-based controllers. Table IV summarizes the performance parameters of the DC link voltage control system under the three different control schemes.

Moreover, to explore the adaptive capability of the proposed AMN controller, it is tested by the reoccurring changes of the DC current injected by the renewable generation system. Further, the performance of the designed controller is investigated and compared with the standard PI controllers. Fig. 7(a) and Fig. 7(b) show respectively the changes of the source DC current and of the active power which could be regarded as disturbance to the control system. The output responses of the three different controllers due to the disturbance are shown in Figs. 8.

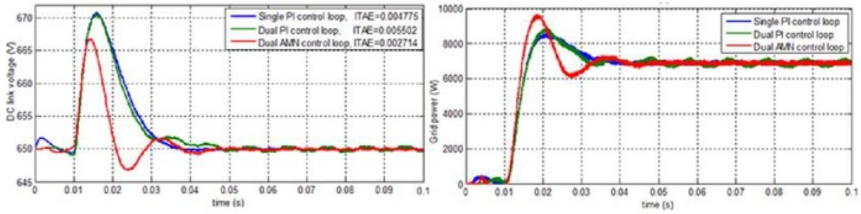
TABLE IV
THE PERFORMANCE OF THE CONTROL SYSTEMS

The performance Parameters	The PI single current loop	The PI double current loop	The AMN double current loop
ITAE	0.009088	0.008513	0.003922
Overshoot (%)	4.15	3.08	2.6
Time setling	0.052	0.048	0.042
Steady state error	0	0	0



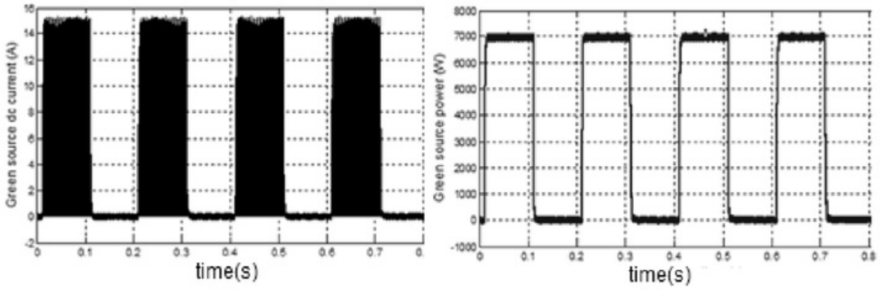
(a) (b)

Figs. 5. The dc current (a) and dc power (b) injected by the RSC to the DC link



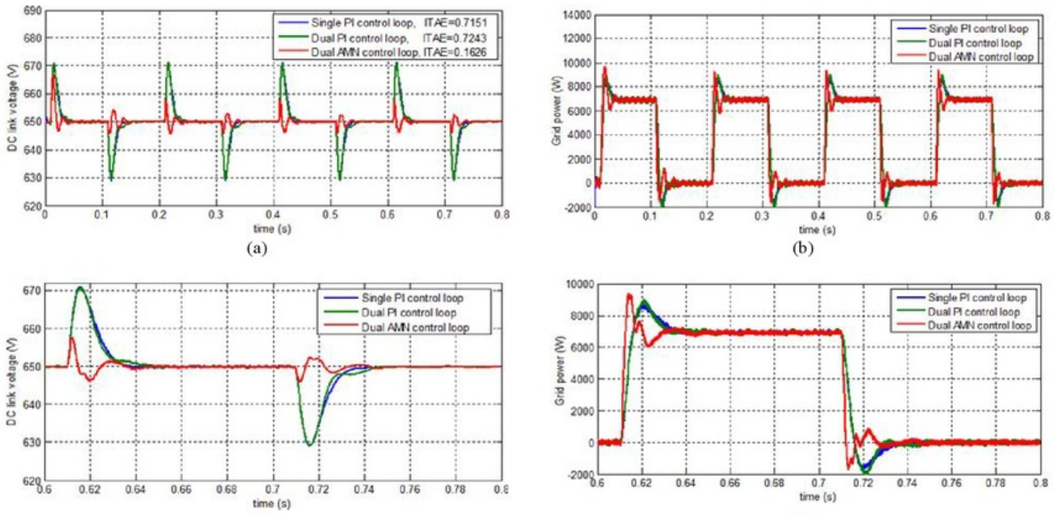
(a) (b)

Figs. 6. Transient response : The DC link voltage (a) The grid power (b)



(a) (b)

Figs. 7. Changes of the dc current (a) and the dc power (b) injected by the RSC to the DC link



(a) (b) (c) (d)

Figs. 8. Transient response : The voltage of the DC link capacitor (a) The grid power (b) The zoomed view of the voltage of DC link capacitor (c) The zoomed view of the grid power (d)

By observing Fig. 8(a) carefully, it can be seen that the overshoot and undershoot of the DC link capacitor voltage under the AMN control strategy for the first disturbance (the first change of the source DC current) are just about 15% lower than those of the standard PI controllers.

However for the second and next disturbances, the overshoot and undershoot of the DC link capacitor voltage are reduced drastically as shown in Fig. 8(c).

From the plot, it can be seen that the overshoot/undershoot reduction are almost 60% compared to those of the optimal PI controllers.

The improvement of the DC link voltage response in transient states under the AMN control strategy basically comes from the AMN capability to remember the previous input disturbances patterns.

From Fig. 8(b) and Fig. 8(d), it can be noted the active power injected to the grid under the three different controllers. As shown in the plots, the AMN controller has a faster transient response compared to the PI-based controllers.

IV.2. Simulation Result under Unbalanced Voltage Condition

The steady state performances of the DC link capacitor voltage and grid power under unbalanced grid voltage conditions basically just depend on the scheme of the inner current control loop.

The control scheme of the outer DC link voltage, in this case will only influence the transient performance of DC link capacitor voltage and grid power. Figs. 9(a), 9(b) and Fig. 9(c) show respectively the steady state conditions of the DC link voltage, the grid power and the grid current under the unbalanced voltage condition in response to 7000 W DC power injected by the renewable power generation system for the three different current control loop schemes.

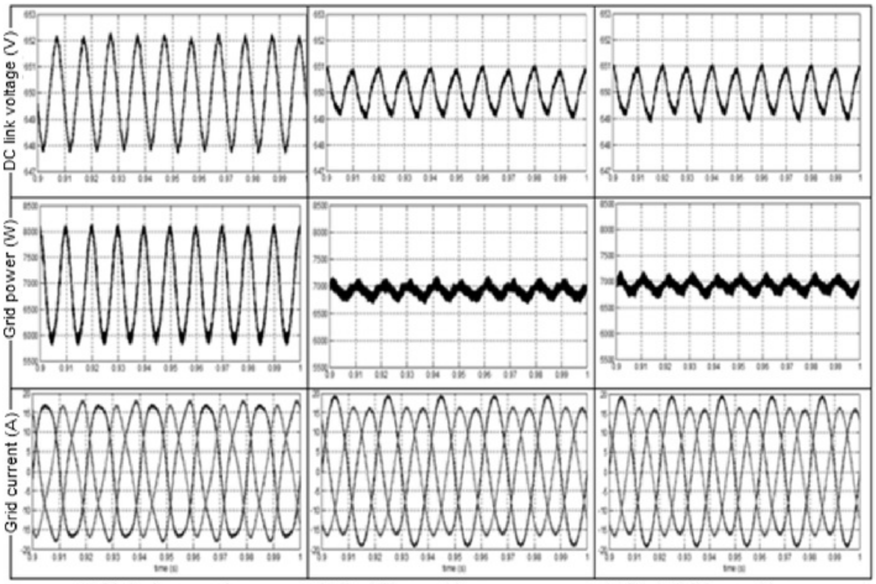
Fig. 9(a) shows the steady state response of the standard PI with inner single current control loop under unbalances grid voltage conditions. From these plots it is shown that the conditions of the DC link voltage and of the grid power of the standard PI single current control loop system will oscillate under unbalanced grid voltage condition; besides the converter system will generate imperfect sinusoidal currents containing many harmonics. These conditions are emerged because the negative sequence of the current component appearing in the unbalanced grid is not controlled.

The different steady state responses under unbalance voltage conditions are shown in Fig. 9(b) and Fig. 9(c).

These plots are resulted respectively from the AMN and PI dual current control loop. By a careful inspection, the steady state performance of these two controller is almost similar; in this case, the oscillation of the DC link voltage and grid power under unbalanced grid voltage condition is much lower compared with that of standard PI single current control loop. This is due to because both the positive and negative components of the converter currents are controlled independently. As shown in the plots, the dual current control loop scheme in this case has the capability to generate the unbalanced harmonic-free grid current. Although the steady state performance of the DC link capacitor voltage and of the grid power under unbalanced grid voltage conditions for the PI dual current control loop and the AMN control system are relatively the same (as shown in Fig. 9(b) and Fig. 9(c)).

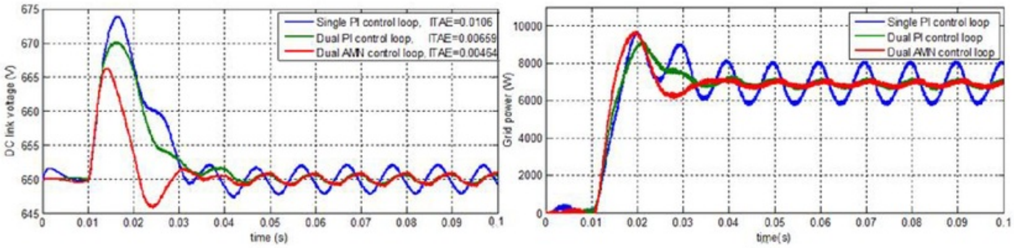
However in the transient state, the performance of the AMN controller under unbalanced grid voltage conditions with dual current control loop is more superior compared to the standar PI-based controllers.

Fig. 10(a) and Fig. 10(b) show respectively the transient response of the DC link capacitor voltage and grid power due to a sudden change of the DC current generated by the renewable power generation system for the three different control schemes. If observed carefully, the transient performances of the three different control strategies under unbalanced grid voltage conditions are relatively the same with that of the controller under balanced grid voltage conditions (Figs. 6). However due to unbalance voltage, the responses of the DC link voltage and grid power in Figs. 9 will be oscillated (with different magnitude) shortly after the transient state passed.



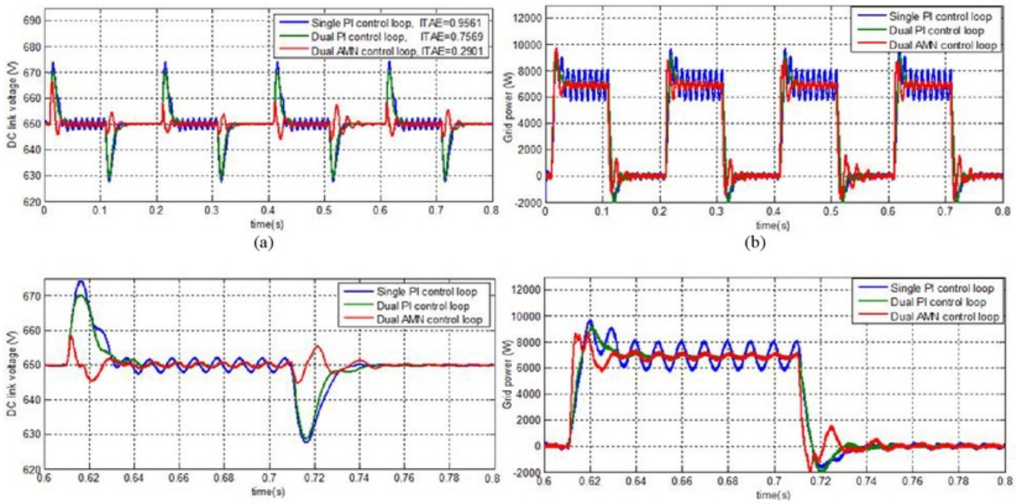
(a) PI single current loop (b) Dual PI control loop (c) Dual AMN control loop

Figs. 9. Steady state response of the three different controller



(a) (b)

Figs. 10. Transient response : The DC link voltage (a) The grid power (b)



(a) (b)

(c) (d)

Figs. 11. Transient response of the voltage of DC link capacitor (a) The grid power (b) The zoomed view of the voltage of DC link capacitor (c) The zoomed view of the grid power (d)

Figs. 11 show the transient states of the DC link capacitor voltage and grid power under unbalanced voltage conditions due to the changes of the DC current injection for the three different control scheme. Almost similar to the previous results (Figs. 8), the overshoot and undershoot of the DC link capacitor voltage and the grid power for the second and next disturbance pulses are more reduced compared to the first disturbance.

Referring to the zoom of the plot in Fig. 11(c), the AMN control system in this case is able to reduce the overshoot of almost 60% lower compared to the optimal PI controller. This capability actually comes from adaptive properties and associative properties of the AMN.

V. Conclusion

The combination of a simple proportional gain controller and B-Spline Associative Memory Networks (AMN) for regulating the DC link capacitor voltage of grid-connected renewable energy systems under generalized unbalanced grid voltage conditions has been proposed in this paper. By utilizing a dual current control loop scheme in which positive and negative sequence of the converter current are controlled independently, the proposed controller in the steady state is able to reduce the fluctuation of the DC link voltage and the oscillation of the injected active power due to unbalanced grid voltage conditions. Whereas, in the transient state, the proposed AMN controller could effectively reduce the overshoot and the undershoot of the DC link capacitor voltage due to sudden changes of the power generated by renewable energy systems. Although without a training phase, the performance of the proposed controller is more superior compared to a standar PI controller with Symmetric Optimum controller parameters, besides the ITAE performance index is smaller and the overshoot/undershoot in transient states resulted by the AMN controller is more reduced.

For the initial condition in which the control system starts to operate, the overshoot/undershoot resulted by the proposed controller in the response to an input power change are about 15% lower compared with those resulted by the optimal PI controller. As it can be seen from the simulation results, the transient performance of the proposed controller will improve drastically if the changes of the power have relatively the same pattern of the previous ones. In these cases, the proposed controller is able to reduce the overshoot of almost 60% lower than that of the optimal PI control system both in balanced and unbalanced grid voltage conditions. Consequently the overvoltage of the DC link capacitor due to abrupt changes of the active power generated by renewable generation systems could be effectively avoided.

Like the other control approaches, the performance of the proposed controller basically depends on several control parameters. For the chosen basis function order, the transient performance of the proposed control system strongly depends on a chosen simple proportional gain (K_p) and a learning rate of the AMN (α). In this work, the K_p parameter is determined by using the Symmetric Optimum method, whereas the appropriate learning rate parameter of the AMN in the proposed controller is still choosen empirically. In future works, the optimal values of the proposed control parameters will be the main investigation.

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4

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