PERFORMANCE IMPROVEMENT OF PMSG WIND ENERGY SYSTEMS BY USING CONVERTERS CONTROLLED BY FINITE CONTROL SET MODEL PREDICTIVE CONTROL

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Abstract: In this paper performance comparison of NPC (Neutral point Clamped) Inverter and TLB (Three level boost converter) for PMSG (Permanent Magnet Synchronous Generator) based WECS (Wind Energy Conversion Systems) using FSC-MPC (Finite Control Set- Model Predictive Control) and Carrier based PWM control is presented. The generator side three-level boost converter carries out the MPPT and balancing the voltages of DC-link capacitor, whereas the grid side NPC inverter, stabilizes the voltage at the DC-bus and reactive power towards the grid. A Model predictive control procedure was proposed as an alternative to the conventional carrier based PWM scheme to decrease switching losses and to obtain a fast-dynamic response. To control the entire system, this method was proposed and to calculate the future performance of control variables, different time prototypes of the defined power electronic converters are used. By using two different cost functions predictions are calculated, and for converters the switching states which can reduce the cost functions are applied. The performance has been tested on 3-MW/3000-V/577-A PMSG in MATLAB/Simulink software.

Key words: Wind Energy; DC-AC power conversion; AC- DC power conversion; PMSG; Boost converter; NPC Inverter; Medium Voltage (MV); FCS-MPC; current control; Passive front-end (PFE); Active front end (AFE); WECS.

1. Introduction

Wind energy is clean, sustainable and is one of the rapidly growing renewable energy source compared to conventional sources of energy [1]. At the same time, there has been a fast development of variable speed WECS using PMSG, full-scale power

converters and gearless drive train for MegaWatt (MW) level wind energy systems [2], [3].To shrink the cost and to boost the efficiency of WECS distinct

generator–converter designs have been established [4], [5], [20]. These configurations are achieved depending on medium voltage (MV) against low-voltage (LV) operation and PFE versus AFE configurations.

For most several kilowatt (up to 0.75MW) LV PMSG WECS, 2-level voltage source converters with back-to-back (BTB) configurations are mostly used [6], [7]. For power rating, more than 0.75 MW, by paralleling the power converters [8], [9] the power and current capability increased. However, this design has several drawbacks such as, decrease in reliability, less efficiency & high cost. To avoid this problem an alternative solution is to use MV BTB NPC converters which are most reliable, compact and adequate.

The power flow is always unidirectional in WECS Since, PMSG don't need any magnetizing current [10],[11], PFE converter can be used instead of an AFE converter as diode rectifier is available in low-cost and naturally more stable compared to the PWM controlled rectifier [12].

In view of MV technology and PFE converters success in the market, an advanced converter arrangement, using a diode rectifier, NPC inverter and TLB converter to high Power MV-PMSG based WECS [13] was proposed. In this system, the balancing of the voltages at the DC-link capacitor can be achieved by TLB and also MPPT is attained by tracing the reference inductor current. The total voltage at the DC-bus and the grid reactive power is controlled by NPC inverter.

FCS-MPC is a simple and powerful control method that has been newly applied to power converters. This method is easy to execute, intuitive and it can be employed for different systems by introducing simple nonlinearities and/or limitations. The conventional carrier based PWM scheme is also used most which can satisfy the control requirement under normal operating conditions. However, systems performance will decrease, such as higher switching losses, slow dynamic response, higher THD in grid currents, etc.., to avoid these problems we use predictive control technique. To show the superiority of this method, a comparative study FCS-MPC and the conventional carrier based PWM techniques and simulation results are presented.

2. Control System for The PMSG WECS

The block diagrams of the two control schemes are shown in fig 1&2. In this paper, a comparison of PWM technique with FCS-MPC for PMSG based WECS is presented. Because of the decoupling nature of the NPC inverter and TLB converter, two individual control loops exist.

2.1. DC-Link MPPT Control Technique

Depending on power curves MPPT block gives reference power by using following expression,

$$P^* = \frac{1}{2}\rho A v_w^3 C_P \qquad ----(1)$$

The active power can be regulated by adjusting the DC-link current i_{dc} using a PI controller because active power is a product of DC-link input current and voltage i.e., the duty cycle D_1 regulates the active power of WECS. The TLB boost nature can be defined as follows,

$$\frac{v_{dc}}{v_{in}} = \frac{1}{1-D_1} \qquad ----(2)$$

For $0 \le D_1 < 1$

The generator speed varies with time, so the input DC-voltage v_{in} is uncontrollable. The error duty cycle is produced by the second PI controller as follows,

$$\Delta D = \left(\frac{k_1 + k_2}{s}\right)(v_{c1} - v_{c2}) ----(3)$$

Where, $\Delta D = \left(K_1 + \frac{K_2}{s}\right)$ is PI controller transfer function. The neutral point balancing is controlled by duty cycle D_2 as follows,

$$D_2 = D_1 + \Delta D \qquad ----(4)$$

In this a simple phase shifted PWM technique is used to produce pulses to the TLB converter.

2.2. Decoupled voltage oriented control (VOC) of NPC inverter:

The main aim of this controller is to control the voltage at the DC-link v_{dc} and the grid reactive power Q_g separately. To achieve this, the decoupled VOC scheme is used. In this scheme, there are two inner current loops to control the line currents i_{dg} and i_{qg}, and one outer voltage feedback loop to control the DC voltage v_{dc}. The three-phase line currents i_{ag}, i_{bg}, and i_{cg} are converted into the 2-phase currents, i_{dg} and i_{qg} with an appropriate grid voltage orientation. The independent control of these 2 components gives a constructive method to regulate the system reactive power and DC voltage independently. The decoupled controller output is as follows,

$$\left.\begin{array}{l} v_{di} = -(k_1 + k_2/s)(i_{dg}^* - i_{dg}) + \omega L i_{qg} + v_{dg} \\ v_{qi} = -(k_1 + k_2/s)(i_{qg}^* - i_{qg}) - \omega L i_{dg} + v_{qg} \end{array}\right\} --------(5)$$

A simple level shifted PWM with 3rd harmonic injection is used to control the neutral point.

2.3. TLB converter Predictive Control

The voltage at the DC-link is considered as a steady voltage source because the NPC inverter manages well the total voltage at the DC-bus[14],[15]. The electromagnetic torque and the stator currents of the PMSG are controlled properly by regulating the gating signals of the TLB converter based on the above condition. Procedure for gating signal generation for TLB converter is as follows,

- The initial step is to evolve an MPPT algorithm for TLB converter. To allow the operation of variable speed WECS, MPPT

method is used. Optimum power control MPPT technique [16] is used in this paper which is simple and reliable.

- By using the rated turbine parameters, evolve a look-up table which consists of generator mechanical speed (w_m) versus output power reference. By the shaft encoders measure the mechanical speed $w_m(k)$.
- By the developed lookup table, we get $p_{dc}^*(k)$.
- Power is the product of voltage and current (p=v*i). Dividing the input reference power $\left(p_{dc}^*(k) \right)$ with the voltage calculated at the

input [vin(k)] the reference DC-inductor current [$i_{dc}^*(k)$] can be attained. This reference current $i_{dc}^*(k)$ changes with the wind speed. So, the MPPT procedure can be attained by capturing the wind Speed at different Conditions.

- By using present and past samples [17],[18], find the future reference Dc-current value.

$$i_{dc}^*(k+1) = 4i_{dc}^*(k) - 6i_{dc}^*(k-1) +$$
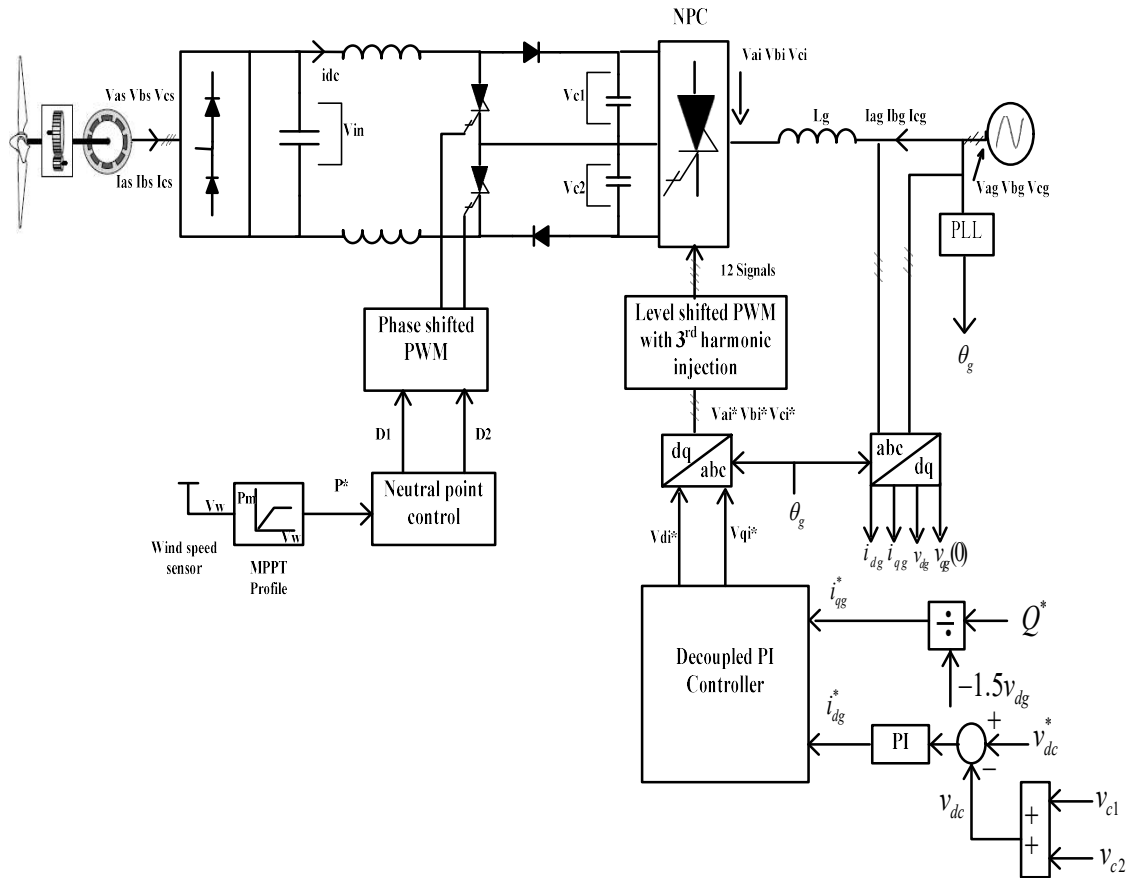
$$4i_{dc}^*(k-2) - i_{dc}^*(k-3) \qquad ----(6)$$

Figure 1. DC-link MPPT control for MEDIUM VOLTAGE PMSG WECS

- Compute the gating pulses of NPC inverter and 3-phase currents at the grid at [k^{th}] sampling instant idc(k), $v_{c1}(k)$,$v_{c2}(k)$,and $v_{in}(k)$.
- TLB converter cost function is as follows,

$$g_t(k) = \left[i_{dc}^*(k+1) - i_{dc}(k+1) \right]^2 + \lambda_{dc,b} * \left[v_{c1}(k+1) - v_{c2}(k+1) \right]^2$$

$$+\lambda_{swc,b} * \sum_{j=1,2} \left| s_{jt}(k) - s_{jt,op}(k) \right| ----(7)$$

Where $\lambda_{dc,b}$ = weighing factor balancing the DC-link capacitor voltages

$\lambda_{swc,b}$ = weighing factor of the switching frequency reduction.

$s_{1t}(k)$ and $s_{2t}(k)$ are the gating signals which are predicted.

$s_{1t,op}(k) = s_{1t}(k-1)$ and $s_{2t,op}(k) = s_{2t}(k-1)$ are the optimal previous sample gating signals.

- For every sampling time, switching pulses $s_{1t}(k)$ and $s_{2t}(k)$ which reduces the cost function (7) is selected and given to TLB converter. PWM modulators and linear regulators are eradicated by this approach.

The primary target is to keep the voltages of DC-link capacitors well balanced. To maintain float in the voltages of the capacitor likely 1.9% of its minimal voltage at the DC-link, select $\lambda_{dc,b} = 1$ in the first sample and lower the value in steps.

The secondary goal is to minimize the switching frequency. The minimization of the switching frequency can be achieved by taking $\lambda_{swc,b} > 0$, but there is an imbalance in voltages at the capacitors and complex inductor tracing error. When there are more control variables for a cost function, compared to absolute cost function, quadratic cost function is superior [19].

2.4. NPC inverter predictive control

In observation of NPC inverter, the voltage at the DC-link is considered as fluctuating DC current source. The grid reactive power and total voltage at the DC-bus are controlled with proper controlling of the gating signals of the NPC inverter. Procedure for the control system execution is as shown below,

- Calculate the currents, grid voltages and voltages at the DC-link and Using a PLL, find the angle of grid voltage, θ_g.

- Transform calculated grid currents & voltages to and synchronous (dq) reference frame and stationary (αβ).

- From v_{dc}^* and ϱ_g^* loops produce i_{dg}^* and i_{qg}^* respectively.

- Using the angle of a grid voltage θ_g, transform the SRF references (i_{dg}^* and i_{qg}^*) to the stationary frame ($i_{\alpha g}^*$ and $i_{\beta g}^*$).

- For stationary frame variables [18], extrapolation of vector angle is the better way. The future values of the grid currents are estimated as follows,

$$\begin{bmatrix} i_{\alpha g}^*(k+1) \\ i_{\beta g}^*(k+1) \end{bmatrix} = e^{jw_g T_s} \begin{bmatrix} i_{\alpha g}^*(k) \\ i_{\beta g}^*(k) \end{bmatrix} \quad ----(8)$$

Where ω_g is the grid angular frequency.

The grid side cost function is as shown below,

$$g_i(k) = \left[i_{\alpha g}^*(k+1) - i_{\alpha g}(k+1) \right]^2 + \left[i_{\beta g}^*(k+1) - i_{\beta g}(k+1) \right]^2 +$$
$$\lambda_{swc,i} * \sum_{j=1,2} \sum_{x=a,b,c} \left| s_{jx}(k) - s_{jx,op}(k) \right| ----(9)$$

Where $\lambda_{swc,i}$ = the switching frequency weighing factor for decrement of the NPC inverter.

- For each sampling time, the switching state which reduces cost function (9) is selected and given to NPC inverter.

Weighing factor selection is same as the TLB converter. In this inverter cost function, the DC-link voltages do not take into consideration. The computational burden is low in this inverter because the cost function has less number of objectives.

Table 1. 3MW/3000V/53.33HZ PMSG Parameters

Rated output power	3.0MW
Rated mechanical shaft input power	3.02838MW
Rated apparent power	3.6373MVA
Rated line-line voltage	3000V(rms)
Rated phase voltage	1732.05V(rms)
Rated stator current	700A(rms)
Rated stator frequency	53.33HZ
Rated power factor	0.8248
Rated rotor speed	400rpm
Number of pole pairs	8
Rated mechanical shaft input torque	72.2972KN-m
Rated rotor flux linkage	4.3034 Wb (rms)
Stator winding resistance	19.28mΩ
d-axis synchronous inductance	4.1753mH
q-axis synchronous inductance	4.1753mH

Table 2. Grid and filter parameters

GSC apparent power SB	3.0MVA
Grid phase voltage VB	1732.05V (rms)
GSC rated current IB	577.4 A (rms)
GSC switching frequency	2000HZ
Filter resistance	0.015Ω

Filter inductance	1.6mH

Table 3. Three level boost converter parameters

Input capacitor, Cin	3500μF

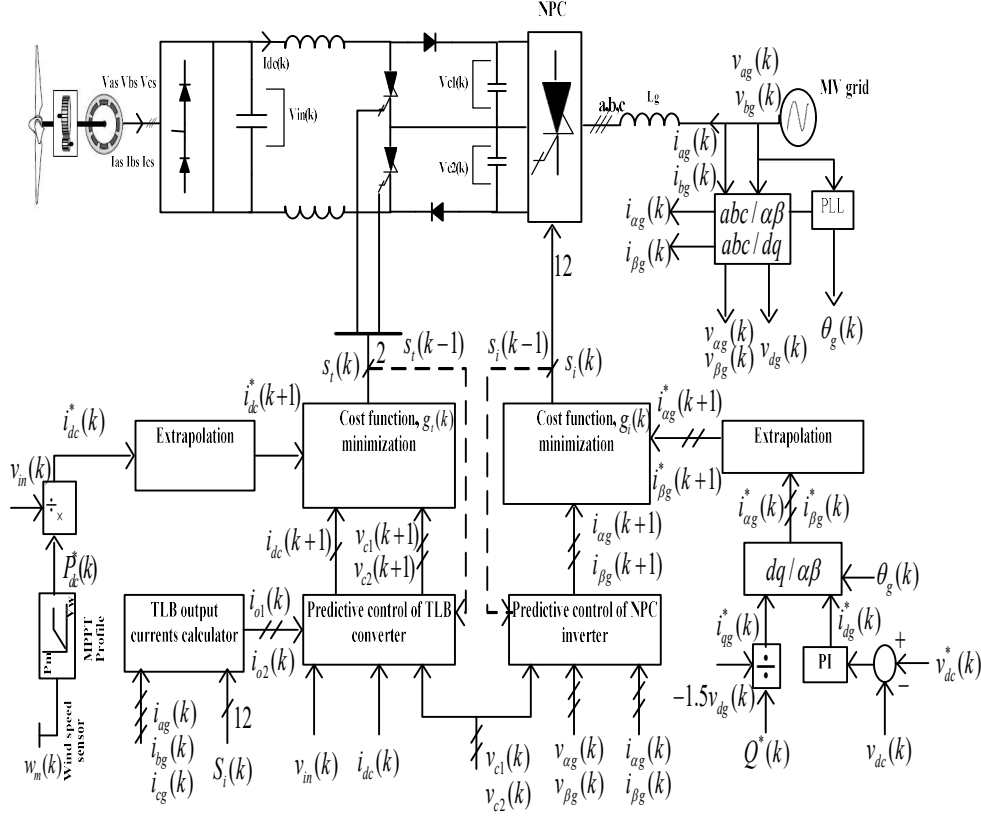|	
Output capacitors, C1&C2	3500μF
Inductors L1 & L2	8mH
Switching frequency	2000 Hz

Fig. 2. MPC scheme for TLB converter-and NPC inverter for PMSG based WECS

3. Simulation Results

Fig. 1 and 2 represents the power converter topology and control method which were simulated with the 3-MW/3000-V/577-A WECS arguments as denoted in the Table 1, 2, 3 by using MATLAB/Simulink. Fig. a, b represents simulation waveforms with different speeds of wind. 12m/s is taken as wind speed and generator functions at rated speed. Because of the diodes natural commutation, the stator voltage and current waveforms of the PMSG are crippled. The in-phase fundamental stator current and voltage helps PMSG to operate at unity power factor. The three-phase currents contain harmonics at the generator side which causes ripples in electromagnetic torque. TLB converter maintains current idc of DC-link at its basic value, while inverter on the grid side controls the reactive power and net DC-bus voltage at reference values. Primary point to note is that the mechanical input power (3 MW) is always higher than the rated output power of the generator. Switching frequencies of the NPC and TLB converter inverters are 900 and 1400 Hz, under the active condition, respectively

At 0.5s, a step-by-step adjustment in the wind speed is given from 12 m/s to 10.8 m/s. After short transient period the generator current, torque, speed and the TLB converter input voltage settled to a new working point. Change in speed of the generator, lead the MPPT procedure to generate a DC current new reference value, and the controller contrived the inductor current to route back to its reference, which means that MPPT is acquired with a change in wind speed. The magnitude of the grid current (40A) and thus the active power given to grid (1.99MW) are altered accordingly with variable wind speed condition. Respective switching frequencies of NPC inverter and TLB converter and are 890 and 1022Hz.
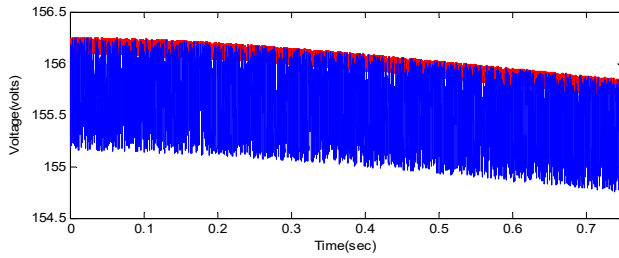
During all circumstances, even during transient conditions: 1) the idc track its reference value, 2) Better balanced voltages of capacitors 3) the total voltage of DC-bus is managed at reference value, 4) reactive power is provided as needed by the grid operative.
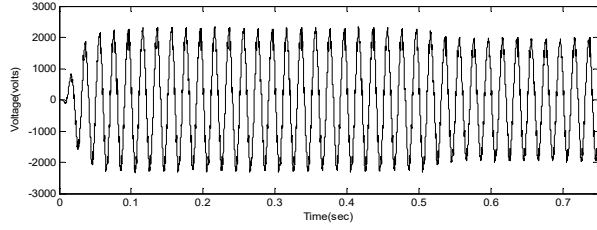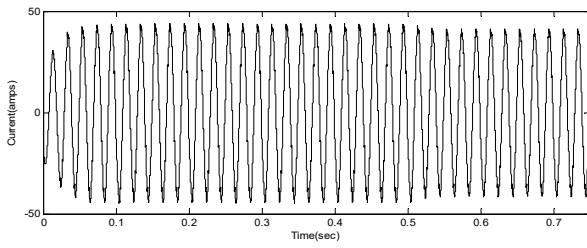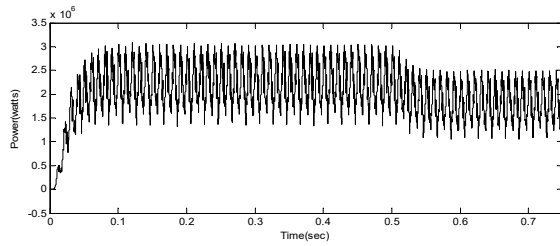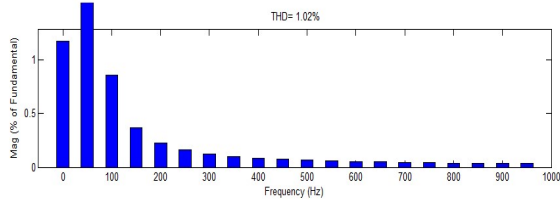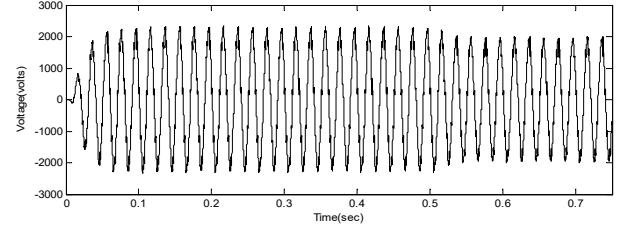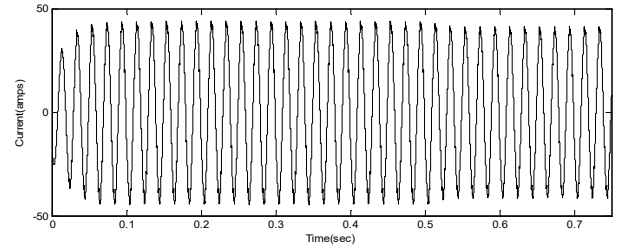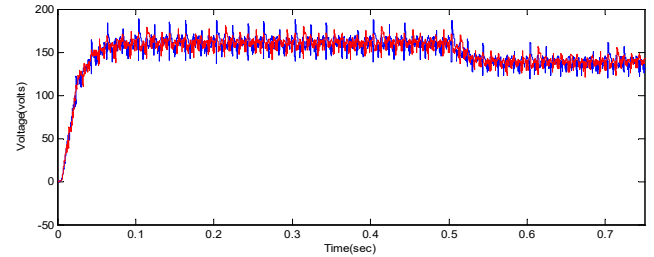
Fig. a) PWM Method: (i) phase-a grid voltage (ii) phase-a grid current (iii) capacitor voltages V_{c1}, V_{c2} (iv) active power (v) FFT for grid-a current

(i)

(ii)
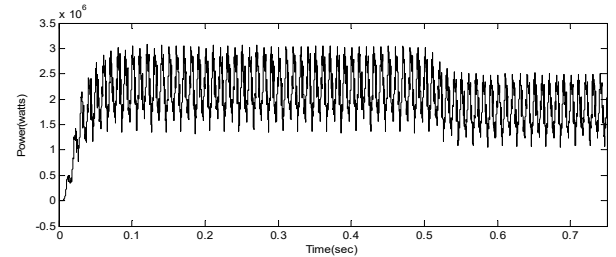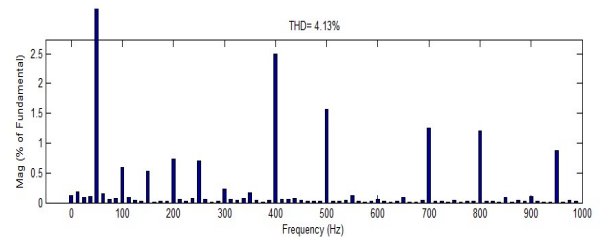

(iii)

(iv)

(v)

(i)

(ii)

(iii)

(iv)

(v)

Figure. b) FCS-MPC Method: (i) phase-a grid voltage (ii) phase-a grid current (iii) capacitor

voltages V_{c1}, V_{c2} (iv) active power (v) FFT of grid-a current

4. Conclusions

For huge power PMSG-WECS, a medium voltage converter scheme which consists of diode rectifier, NPC inverter and TLB converter are proposed. This configuration merges the advantages of grid-side multilevel and generator-side PFE operation. Compared with the BTB-NPC inverters the medium voltage operation of the WECS gives more reliable, simple and low cost solution. In the conventional control method the DC-link voltages are un balanced so by the predictive control technique the voltages of DC-link capacitors are well stabilized by the TLB converter during all performing conditions, and thus, there is no need to establish a convoluted control system for the NPC inverter to hold the voltages of DC-link capacitors balancing function.

The count of switching states is less in predictive control technique compared with the conventional method and thus, the switching losses are less. Adopting the discrete-time exemplary of the system, 2 separate control loops are implemented, and they produce the gate pulses to the TLB converter and NPC inverter depends on the reduction of cost functions. The dynamic response is acquired by eradicating the utilization of linear controllers and modulation stage with the FCS-MPC procedure. The MPPT and voltages at neutral point are completely regulated by the TLB converter, while the total voltage of the DC-bus and reactive power are controlled by the NPC inverter. By observing the simulation results, the system control goals are attained by an FCS-MPC method which performs very well.

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