Model Based Predictive Direct Speed Control with FCS of PMSM Drive System

G.vijayakumar[1], M.gopi siva prasad[2]
[1]PG-Student, Dept of Electrical and Electronics Engineering, Siddharth institutions of engineering College ,puttur,India,[2]Working in the Dept of EEE at Siddharth institutions of Engineering College, puttur, India.
(vijayakumarg234@gmail.com, gopieps@gmail.com)

Abstract: **Servo drives and drives for position control require a high dynamic on speed control. In this paper, model predictive direct speed control (MP-DSC) is proposed, which overcomes limitations of cascaded linear controllers. The novel concept predicts the future current and speed states in discrete steps and it selects plant inputs which depend mainly on the predicted speed error. Secondary control objectives, such as maximum torque per ampere tracking are included. MP-DSC uses the finite control set approach which makes it suitable for online predictions with a prediction horizon of a few sample periods. The concept has been developed by simulation and evaluated on an experimental test bench. The overall control behavior is evaluated applying reference and disturbance steps to the system, where MP-DSC shows promising results. A solution for disturbance (e.g., load toque) rejection is proposed, and the effectiveness to avoid control offsets is shown. Furthermore, the dynamic performance and the steady-state behavior of MP-DSC is evaluated and discussed.**

Keywords: *Direct speed control, model predictive control (MPC), permanent magnet synchronous machine (PMSM).*

I. INTRODUCTION

Servo drives and drives for position control require high dynamics on speed control. Cascade linear controllers have a limited bandwidth in order to avoid large overshoots and ringing and due to their
Cascaded structure, where the different loops are decoupled in bandwidth. These structures limit the dynamics above all in high power applications, where the switching frequency is low. In these cases, the bandwidth of the current controllers is already low resulting in a fairly modest speed (or position) control dynamic.

In order to increase dynamics, different predictive control approaches have been Investigated in Past and they are shown in the literature. Examples are deadbeat, hysteresis based, trajectory-based control or combinations of the concepts like sliding mode and direct torque control. However, most concepts which have been presented in the literature focus either on current or torque/flux control, which still requires a cascade speed loop. These limitations are overcome with direct speed control approaches.

In contrast to the cited concepts, model predictive control (MPC) can take into account constraints and nonlinearities of multiple input and multiple output plants and handle them in a unified manner. MPC can be divided in continuous control set and finite control set methods. The latter one needs in contrast to the first one no modulator like space vector modulation (SVM) or pulse-width modulation (PWM)] and it is suitable for online optimization. On the other hand, it has a variable switching frequency.

In this paper, the (finite control set) model predictive direct speed control (MP-DSC) is proposed, which overcomes limitations by cascaded loops resulting in high-speed control dynamics (see the controller is based on the finite control set (FCS). MPC approach, i.e., the switching states of the power electronic converter is taken into account and a modulation scheme is avoided. A novel cost function is proposed

In this paper for direct speed control subdivided in a tracking component, an attraction region, and limitations. The tracking component is used to track the reference value. Plant limits are included in the model, and inputs which would lead to a violation of those limits are avoided. Besides speed control, secondary control goals, e.g. concerning efficiency can be included in using control formulation. The attraction region becomes important when the tracking component is small steady state. Moreover, a new way for disturbance and noise rejection is proposed. It improves above all the steady-state performance. Control offsets and switching due to measurement noise are avoided. Moreover, a switching state graph, which is known from model predictive direct current control (MP- has been introduced for keeping the switching frequency of MP-DSC low. Another benefit of the graph is the reduction of the computation time.

This paper is organized as follows the plant is analyzed and shown in, where also the main control goals are defined. MP-DSC is synthesized and the required techniques are shown: past input compensation, state prediction, disturbance handling, state limitations, and the plant input selection via cost function. Furthermore, MP-DSC is tested and the results are shown the overall control behavior is evaluated such as the control offset suppression, the dynamic and steady-state behavior.

II. ANALYSIS

A. *Model plant*

The continuous time, permanent magnet synchronous machine (PMSM) model, which works with isotropic (or surface) and anisotropic PMSM, is in the dq reference frame

G.vijayakumar[1], M.gopi siva prasad[2] [1]PG-Student, Dept of Electrical and Electronics Engineering, Siddharth institutions of engineering College ,puttur,India,[2]Working in the Dept of EEE at Siddharth institutions of Engineering College,. puttur,India (vijayakumarg234@gmail.com, gopieps@gmail.com

$$i'_d = -\frac{R}{L_d} i_d + \frac{L_q}{L_d} w i_q + \frac{1}{L_d} u_d$$

$$i'_q = -\frac{R}{L_d} i_d - \frac{L_d}{L_q} w i_d + \frac{1}{L_q} u_q - \frac{\lambda}{L_q} w$$

$$T_e = \frac{3}{2} p(\lambda i_q + (L_d - L_q)\, \mathrm{i}_d\, i_q)$$

$$w' = -\frac{B}{J} w + \frac{p}{J} T_e - \frac{p}{J} T_l$$

The model can be rewritten in discrete time. The electrical state-space model is obtained only discrete analysis only the maximum possible switching frequency is limited by the computing time of the algorithms which determine the optimal control systems

Higher frequencies can be handled by employing the double prediction method.

$$T_e(k) = \frac{3}{2} p(\lambda i_q(\mathrm{k}) + (\mathrm{L}_d - L_q)\, \mathrm{i}_d(\mathrm{k})\, \mathrm{i}_q(\mathrm{k}))$$

The discrete mechanical state-space model is

$$x_m(k+1) = \mathrm{A}_m\, x_m(k) + \mathrm{B}_m\, u_m(\mathrm{k}) + \mathrm{E}_m\, w_m(k)$$

$$y_m(k) = C_m x_m(k)$$

$$A_m = 1 - \frac{B T_s}{J} \quad B_m = \frac{p\, T_s}{J}$$

$$C_m = 1$$

B. Controller block:

The minimum requirements on a controller of a discrete time system is, besides practical asymptotic stability the tracking Moreover, a plant has limits for the states and inputs. MPC takes implicitly input limits into account but the states must be limited to their rated values x (k) ≤ x_r where x_r ▯ R_n.

In this paper, the x_m is assumed to be limited externally by limiting the reference value. On the other hand, the electrical states, i.e., the current amplitude must be limited to the maximum admissible

Additional demands on the control algorithm may arise. For Example, high current quality leads to a small toque ripple, or the machine should work close to the maximum torque per ampere (MTPA) trajectory in order to obtain a high steady state. Equilibrium condition efficiency, if over-speed must work off the MTPA trajectory in order to weaken the stator flux.

$$T_e(\mathrm{k}) = \frac{3}{2} p(\lambda i_q(\mathrm{k}) + (\mathrm{L}_d - L_q)\, \mathrm{i}_d(\mathrm{k})\, \mathrm{i}_q(\mathrm{k}))$$

$$u_e = \left[u_d, u_q\right]^T, \quad x_e = y_e = \left[i_d, i_q\right]^T$$

$$x_m(k+1) = \mathrm{A}_m\, x_m(k) + \mathrm{B}_m\, u_m(\mathrm{k}) + \mathrm{E}_m\, w_m(k)$$

$$y_m(k) = C_m x_m(k)$$

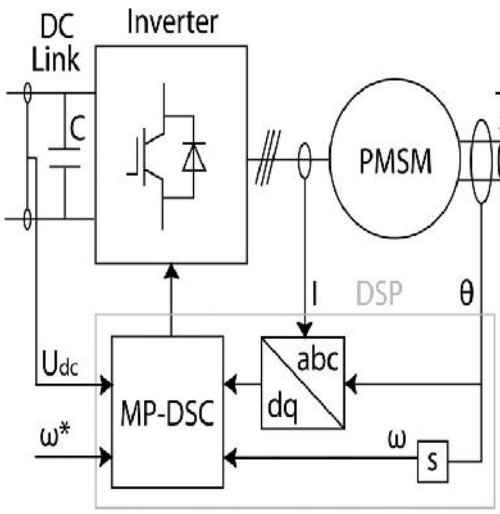

Fig.1. PMSM-VSI drive system

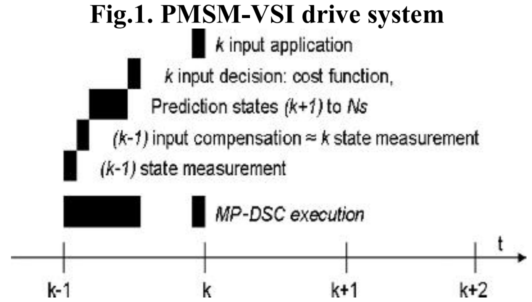

Fig.2.Exeustion of the MP-DSC algorithm

Equilibrium condition efficiency, if over-speed capabilities are desired, the controller must work off the MTPA trajectory in order to weaken the stator flux is obtained.

III. SYNTHESIS

In this section, the execution of the MP-DSC algorithm is shown. The operation can be divided in four main parts: measurement, prediction, input selection, and actuation. First, the necessary states are measured in period (k − 1) and concepts for compensating the delays and rejecting the disturbances are executed. Then, future plant states are computed for the periods (k + 1). . . N. The results are evaluated with a cost function and the input with the lowest cost will be applied in period k.the MP-DSC execution is shown in further reduction of the switching frequency, which may be needed in very high-power applications, can be achieved by defining a current error boundary of rectangular shape

A. Measurement:

The measurements from the previous sampling instant are assumed to be available for control is the following two equations as follows $\mathbf{y_e}$ (k − 1) and y_m (k − 1). The states changes due to the system itself x (k − 1), the inputs u(k−1),and the disturbances w(k −1). Compensation is necessary in order to apply the input u (k) to the state for which it has been computed for. Thus, the model and is used to compute the states x (k) using y (k− 1), u (k − 1), and, if known, w (k−1) where

$$x_e(\mathrm{k}{+}1) = A_e x_e(k) + \mathrm{B}_e\, u_e(\mathrm{k}) + \mathrm{E}_e$$

$$y_e(\mathrm{k}) = C_e x_e(\mathrm{k})$$

***B. Prediction*:**

The possible inputs ue (k) ▯ Ue which can be applied after a given input ue (k − 1) are additionally limited by a switch state graph similar such a graph has several benefits. First, the switching frequency is limited since only one switch state change is permitted per sampling period. The application of two opposite voltage vectors is avoided leading to a lower current ripple. Moreover, the number of predictions, which must be computed, is limited, e.g. (Nu/2) N instead of (Nu) N f Inverter The states xe (k + 1) and xm(k + 2) depend on their previous values and ue (k). Since ue (k) ▯ Ue is a finite number Ni ▯ N0 of ud and uq combinations, the possible future states are a finite set and can be computed. If the prediction horizon is N >1, the future states are used to calculate the states of the prediction period j ▯ N^+, i.e., x_e (k +j) and x_m(k +1+j).The prediction Process can be seen

$$A_e = \begin{pmatrix} 1-\dfrac{RT_s}{L_d} & \dfrac{L_qT_s}{L_d}w \\ -\dfrac{L_dT_s}{L_q}w & 1-\dfrac{RT_s}{L_q} \end{pmatrix}$$

$$B_e = \begin{pmatrix} \dfrac{T_s}{L_d} & 0 \\ 0 & \dfrac{T_s}{L_q} \end{pmatrix} \qquad C_e = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Recursive function, this calls itself until the prediction period is equal to the Prediction horizon. The number of predictions increases exponentially with N. Thus, the choice of N is critical for real-time implementations. Usually the prediction horizon cannot be more than a few samples.

***C. Input selection*:**

The possible inputs u (k) is evaluated using an optimality criterion. Optimality can be obtained only with respect to mathematical criteria, i.e., the cost function, and the input with the best performance, i.e., with the minimum cost, is chosen for application. The recursive prediction algorithm calculates the path with the minimum cost ahead. The cost of the actual prediction period is added to the path with the lowest cost ahead. Thus, the path with the globally lowest cost is constructed. the plant

Tracking model:

The main goal of MP-DSC is the minimization of the speed error. Thus, the cost for a speed error is

$$c_T(k) = (w(k) - w^*(k))^2$$

Attraction region:

If the reference tracking error is large (the main focus of the controller should be the reduction of cT (k). However, when the tracking errors small (approximately, i.e., semi steady-state behavior), secondary control goals can be focused. This behavior is achieved by adding the secondary control goals to the cost function weighting them less than the tracking component. Thus, the system states are "attracted" to the secondary control goals in semi steady-state conditions. Otherwise, the so-called attraction region will be ignored. The attraction region is designed to have influence on the input selection when cT is small. A main steady-state concern is the system efficiency. Low absolute currents are desired in order to avoid large losses, i.e., to obtain a high electrical efficiency for this reason, the MTPA criteria are used

$$c_{A1}(k) = \left(i_d + \frac{L_d - L_q}{\lambda}(i_d^2 - i_q^2) \right)^2$$

$$c_{A2}(k) = \left(\sqrt{\left(\frac{L_q}{L_d} i_d\right)^2 + \left(i_d + \frac{\psi}{L_d}\right)^2} - \frac{\zeta U_c}{\sqrt{3} w L_d} \right)^2$$

Where id, iq are trajectory in space

Control limitation:

Control limitations need to be taken into account when designing the controller. The proposed-DSC uses a concept which is very close to the concept of soft constraints. The controller may violate limits, but any violation is penalized heavily in the cost function. Thus, if a violation happens it lasts only for a short time and generally violation of limits in steady-state conditions is avoided. In practice, the constraints are design as piecewise quadratic functions, which are zero when the limit is not violated and increases quadratic ally i.e. power converter and electrical machine have a maximum absolute current. The plant current must be limited to this value.

$$c_{L1}(k) = \begin{cases} \left(I_r - \sqrt{i_d^2 + i_q^2}\right)^2 & \Big| I_r - \sqrt{i_d^2 + i_q^2} < 0 \\ 0 \end{cases}$$

$$c_{L2}(k) = \begin{cases} \left(2\dfrac{L_d - L_q}{\psi} id + 1\right)^2 & \Big| 2\dfrac{L_d - L_q}{\psi} i_d + 1 < 0 \\ 0 \end{cases}$$

$$c_{L3}(k) = \begin{cases} \xi^2 & | \xi < 0 \\ 0 \end{cases}$$

But only one solution corresponds to the MTPA trajectory. In order to avoid convergence to the wrong solution, the state should remain on the correct side of the symmetry axis for operation at high speeds; the voltage limit must be

D.Cost function

The cost function is defined with

$$c(\text{k}) = \sum_{i=0}^{N} \begin{pmatrix} \lambda_T c_T(k+i) + \\ \lambda_A c_A(k+i) + \\ \lambda_L c_L(k+i) \end{pmatrix}$$

Where λ_T , λ_A, and λ_L are weighting coefficients, which define the importance of a goal with respect to the others

$$\xi = \sqrt{\left(L_q i_q\right)^2 + \left(L_d i_d + \psi\right)^2} - \frac{\zeta U_c}{\sqrt{3}\,|w|}$$

IV. EVALUATION

The concept has been applied to a PMSM-VSI drive system in simulation and on an experimental test bench. The test system characteristics are shown in Table I. The MP-DSC performance has been evaluated and the results are shown in this section. The lowest admissible current should be applied which permits to maintain the speed. Electrical torque is still necessary.

Table 1
Plant data

Control	
Sampling time T_s	$100\mu s$
Prediction horizon N_s	3
Theoretic peak switching freq. f_{swp}	$1.66kHz$
λ_T	1
λ_A	10^{-3}
λ_L	10^4
Encoder (number of pulses)	$2048ppr$
DSP (TMS320F240) freq.	$20MHz$
Max possible N_s (computational limit)	4
Converter	
Type	2-level VSI
DC-link voltage U_{dc}	$200V$
Rated current I_r	$10A$
Interlock time T_i	$1\mu s$
Electrical Machine	
Type	IPMSM
Rated machine speed ω_r	$3000rpm$
ω_r without field-weakening	$1200rpm$
Rated torque T_r	$7.8Nm$
Inductance (d axis) L_d	$12mH$
Inductance (q axis) L_q	$20mH$
Stator resistance R	$636m\Omega$
PM rotor flux ψ	$88mWb$
Pole pairs p	5
Friction constant B	$1.7 \cdot 10^{-3} kgm/s^2$
Inertia constant J	$1.0 \cdot 10^{-3} kgm^2$

A. Speed reference steps

In order to evaluate the control behavior, different speed reference steps have been applied to the system. Above the rated Speed, a negative d current must be injected to weaken testator flux. Otherwise, the stator voltage tends to rise above the rated voltage of the drive and the speed cannot be increased anymore. The drawback is the reduction of the available torque since the current is partially used for flux weakening. Moreover, the field weakening region can be further divided Above a certain velocity, a negative d current is also necessary at steady state for meeting the voltage limit. The first speed reference step is 0–1000 r/min. 1000 r/min is below rated speed and no field weakening is necessary The electric states stay on the MTPA trajectory. The second speed reference step is 1000 to 2000 r/min.

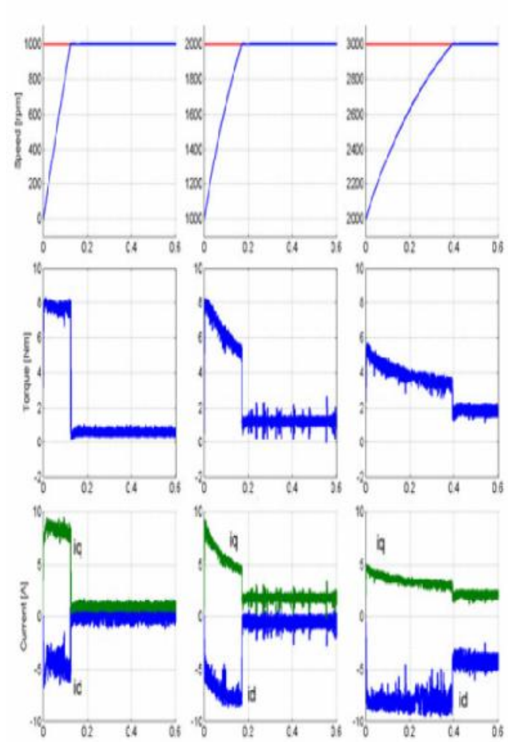

Fig. 3 Simulation result: speed reference steps; from top: reference and measured speed, and electrical torque.

. The electric states stay on the MTPA trajectory. The second speed reference step is 1000 to 2000 r/min. At 2000 r/min, peak torque cannot be obtained any more since it would lead to violation of the voltage limit. However, no d current injection is required for operation at 2000 r/min without load torque. Thus, the step can be seen as step from the standard operation region to the field weakening region. The third step is from 2000 to 3000 r/min. At 3000 r/min, d current must be injected also without producing significant torque in order to fulfill the voltage limit. The simulation results are shown in Fig. 4 and the experimental results are shown in Fig. 5. In this figure, the reference and measured speed is shown. Moreover, the electrical torque, the dq currents, and the switching frequency are shown. When the steps are applied, the tracking component is dominant. Thus, high torque is applied until the speed error becomes small. When this happens, the attraction region becomes important. The lowest admissible current should be applied which Permits to n the speed.

B. Dynamics

The speed control performance of the system is evaluated in this section. Small speed reference steps have been applied to the system. The steps are scaled in order to avoid saturation of the system, in first place the limitation of the torque, i.e., the currents. Since the system is nonlinear, it is difficult to find analytical performance indexes like the high frequency cutoff (which corresponds to the bandwidth due to the low However, a Gaussian response can be assumed in order to give an idea about performance. Thus, the further called practical bandwidth of the corresponding system can be approximated knowing the 10%–90% rise time tr using Fbw =0.34/t_t The step responses have been the average raise times are about t_r = 3 ms

C.Load torque

The main disturbance, i.e., the load torque, tends to lead to prediction errors. Generally, it cannot be compensated since a measured value can be goes to zero.

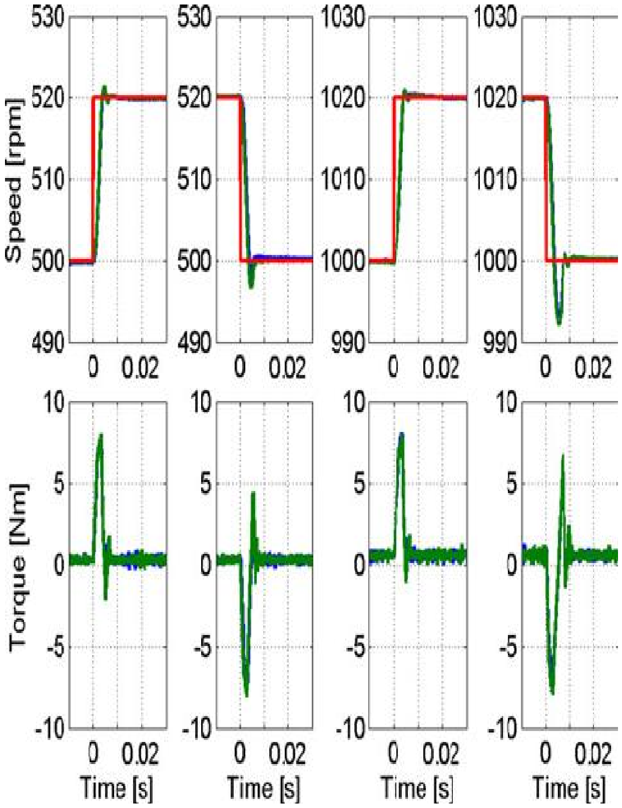

Fig.4 Simulation result: two (blue and green) speed reference steps without torque saturation (20 rpm = 0.6%); from top: reference and measured speed, and electrical torque.

Potential error influences the evaluation using the cost function and results in a speed offset. Of course, such an offset should be avoided. Improvement comes along using the compensation; this is shown. The disturbance is compensated forcing the error between predicted and measured speed to zero.

This implies that the offset in speed regulation is compensated. The concept is evaluated in simulation in Fig. 8 and experimentally in load torque step Tl = 6 N·m (about 80%) is applied at n = 500 r/min. The resulting speed variation is110 r/min (about 3.5%) before it gets compensated. In the figures.the reference and measured speed, the electrical torque, the dq currents, and the switching frequency are shown.

Generally a load torque can obtained from mechanical output of machine it takes source from stator some losses can occurred in it and stator output is can be given to rotor input some rotor losses can be obtained this will cause output may be effect from some losses in this load torque may depend on speed of motor slightly less than the input of the rotor of speed.

D. Torque Quality

MP-DSC does not control explicitly the currents to a sinusoidal Value. Thus, steady-state tests have been performed in Order to show the current torque quality. The load torque Tl = 6 N·m is applied at n = 500 r/min. frequency odd harmonics which are not the multiples of three are observed in the experimental result. However, the magnitudes of both noise and harmonics can be accepted considering the average switching frequency. For both systems, the THD has been computed. It is THD = 5.9% in simulation and THD = 4.7% experimentation. If a higher switching frequency is acceptable the THD can be reduced using a smaller sampling period. In the experimental spectrum, some harmonics are pointed out at 3.3 kHz

This frequency corresponds to the mechanical resonance frequency of the test bench. They are not observed in simulation since the plant has been modeled with a single mass-equivalent system.

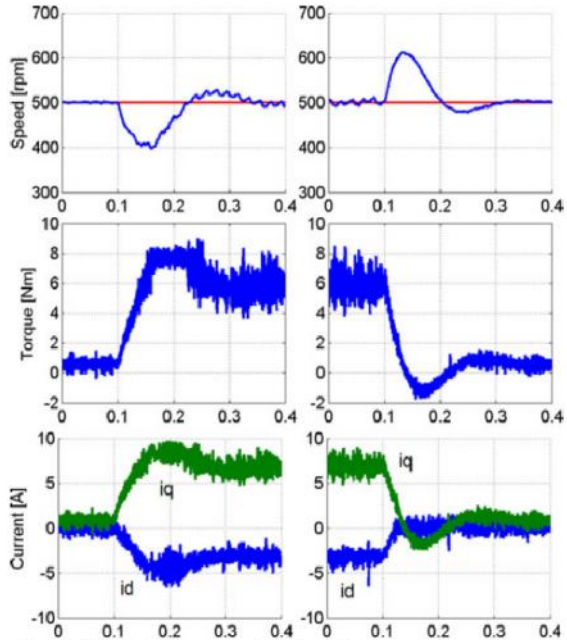

Fig.5 Simulation result: load torque step; from top: reference and measured speed, electrical torque, dq currents, and switching frequency.

E. Spectrum and Switching Frequency

The switching state of the converter is changed at equidistant instants in time, i.e., in each sampling period, an optimal switching state is selected and applied during a whole period. This way, variable switching frequency is obtained, where the maximum switching frequency is limited to half the sampling frequency. The resulting spectrum of the voltages and currents is spread over a wide range of frequencies and will change depending on the sampling frequency and the operating conditions.

This kind of spectrum is not desirable in some applications. In order to get a concentrated spectrum, similar to the one obtained using PWM, a frequency weighted cost function has been proposed in where a narrowband stop filter is included in the cost function. Some other applications may require a reduced switching frequency, in order to reduce the switching power losses. In these cases, a weighting factor related to the commutations can be included in the cost function, as proposed in where it is demonstrated that the average switching frequency can be considerably reduced. A different approach is the use of a constant switching Frequency, as will be explained in the next section. A comparison between the variable and constant switching frequency algorithms is presented in for the power control of an active front-end rectifier.

V. CONCLUSION:

In this research, MP-DSC has been developed and implemented. The concept is based on the MPC approach with finite control set. The possible plant inputs are applied to an online plant model and their effects are predicted, which can be repeated until the prediction horizon is reached.

The results are fed to a decision or cost function, which is used to decide the plant input, i.e., the converter switching state for the next sampling period.

MP-DSC has been evaluated by simulation and the results confirm the dynamic advantages of the concept. The overall control behavior has been evaluated with reference and disturbance steps. MP-DSC shows promising result with respect to both. Moreover, MTPA tracking is obtained and leads to high efficiency. The major plant disturbance, i.e., the load torque, would lead to a prediction and, thus, to steady-state speed offsets.

A compensator is proposed and its effectiveness is show The MP-DSC dynamics has been quantified with the approximate bandwidth–rise time relation assuming a Gaussian response system.

The bandwidth without saturation active is in the order of 100 Hz (compared with the switching frequency which is in the order of 1 kHz). However, significant reference or disturbance steps will usually push the torque into limitation which reduces the raise time according to the limit. Furthermore, the steady-state current quality is discussed. The spectra previously show noise, which is obtained due to the stochastic selection of the plant inputs. Some low-order harmonics are pointed out, but the current, i.e., torque quality, can be generally accepted considering the switching frequency

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Author’s profile

1. Mr. Vijaya kumar was born in 1989. He received B.Tech **(**Electrical and Electronics Engineering) from JNT University, Anantapur and pursuing M.Tech (Master of Technology) in SIETK, PUTTUR, CHITTOR (DIST). His area of interests is Network analysis, Electrical Machines.

E-mail id: vijayakumarg234@gmail.com

2. Mr. M.GOPI SIVA PRASAD was born on 02th December 1980, in TIRUPATHI, in Andhra Pradesh. He received B.Tech. Degree in Electrical and Electronics Engineering from RGMCET in NANDYALA, KURNOOL(DIST). He is completed his M.Tech. Degree in ELECTRICAL POWER SYSTEMS in the Department of Electrical and Electronics Engineering in JNTUA. His area of interest Power Electronics, Power compensation, Digital Protection and Renewable Energy Power generation. Working in the Dept of EEE at Siddharth institutions of Engineering College Puttur

E-mail ID: gopieps@gmail.com