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Dynamic Matrix Control Technique (DMC) and its Application to the Switched Reluctance Machine model

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Abstract

This paper describes a Dynamic Matrix Control technique applied to the Switched Reluctance Machine System (SRM). The underlying robust linear controller design of SRM speed control was done with two different approaches. A first attempt based on a Dynamic Matrix Control method (DMC); it includes an optimization tool that consists of a simulation model and an optimization function. A second attempt was made using two conventional PI controllers.

Finally, the response of the SRM system with DMC controller and conventional PI and PI-AW controllers was compared under the normal case (i.e. without the effect of the uncertainty such as disturbance and noise).

Keywords: Model Predictive Control (MPC), Dynamic Matrix Control (DMC), Proportional Integral Controller (PI)**,** Anti-reset Windup PI controller (PI-AW)**,** Switched Reluctance Machine System (SRM)

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تقنية التحكم بالمصفوفة الديناميكية وتطبيقها على نموذج آلة التردد المتغير

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الملخص:

هذا البحث يمثل دراسة تفصيلية للتحكم التنبؤي بطريقة التحكم بالمصفوفة الديناميكية (Dynamic Matrix Control) واختصارا (DMC)، وقد تم تطبيق هذه الطريقة على نظام محركات التردد المتغير (Switched Reluctance Machine) واختصارا (SRM)، ولتصميم متحكم خطي متين لهذا النظام استخدمنا نوعين مختلفين من الحاكمات فكانت الطريقة الأولى المستخدمة هي التحكم التنبؤي (DMC)، وهي من طرق التحكم المثالي (Optimal Control) التي تتضمن خطوات تحسين التحكم بواسطة النموذج الرياضي للنظام المراد التحكم فيه ودالة تحسين الآداء (Optimization Function). أما الجزء الثاني من هذه الدراسة يتضمن تطبيق المتحكم التقليدي (المتحكم التناسبي التكاملي PI) للتحكم في نفس النظام باستخدام طريقتين تقليديتين؛ وأخيرا تمت دراسة استجابة النظام مع وجود المتحكم الأول والثاني ثم الثالث بدون أي تأثيرات خارجية عليه مع مناقشة جميع النتائج بشكل علمي وصولا إلى استنتاجات قيمة تمثل الأهداف المرجوة من هذا البحث.

الكلمات المفتاحية: التحكم التنبؤي (MPC)، التحكم بالمصفوفة الديناميكية (DMC)، المتحكم التناسبي التكاملي (PI)، المتحكم التناسبي التكاملي مانع التراكم (PI–AW)، محرك التردد المتغير (SRM).

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1- Introduction

Model Predictive Control (MPC) refers to a class of optimal control algorithms that compute a manipulated variables profile by utilizing a linear process model, and using this model to calculate that sequence of future control signals or manipulated variables in such a way that it minimize a multistage cost function. This procedure is repeated at each control interval or sampling time with the process measurements used to update the optimization problem [1], [2], [3], [4].

The MPC controller uses a linear transfer function, state-space, or conventional input-output model to represent the processes. These models can be obtained from process tests using time series analysis techniques that do not require a significant fundamental modeling effort [2], [3], [5]. Multivariable processes can easily be handled by superposition of these linear models [2], [4].

In this paper, we will study DMC technique and apply it to a system that used in electric vehicles and industrial systems, which is known as a Switched Reluctance Machine (SRM).

The (SRM) is an extremely simple machine from a construction viewpoint. The rotor has neither magnets nor windings and consists solely of magnetically soft, low loss steel laminations stacked on a shaft. The stator (built from the same material as the rotor) has windings on each pole and one phase of the motor consists of the series connection of the stator windings on diametrically opposite poles. Both the stator and rotor have salient poles, hence, the machine is referred to as being doubly salient [6].

2- The Switched Reluctance Machine Model

The linear SRM system used in this paper was studied in a previous research published in 2021 [7]. The SRM used is 12/8 pole as shown in figure (1), so we will not detail how to derive the dynamic model of this system, and we satisfied the transfer function that was extracted in that study, which was as follows:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{52.77}{s+4.964} \tag{1}$$

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Where,

Y(s) is the real physical speed [rpm].

U(s) is the manipulating input applied to SRM.

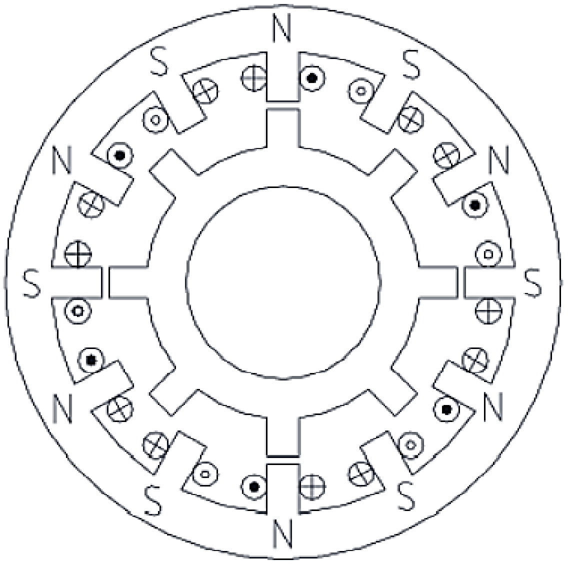

Figure (1): SRM 12/8 pole schematic.

3- Principle of Dynamic matrix control (DMC)

DMC is part of the first generation of MPC, it was proposed by *Catler and Ramakter* in the end of seventies of last century, and has been widely accepted in the industrial world, mainly by petrochemical industries [5], [8].

DMC as all MPC algorithms uses a dynamic model of the plant, along with the current state of the plant to predict the future response. The control algorithm then compares this predicted output to the desired set point trajectory to calculate the control action. The DMC algorithm uses a step response of the plant to predict the future response and minimizes the future error over a set prediction horizon [5], [9], [10], [11].

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The future behavior of the system output is predicted based on a system model and available past data. The future control signal is then calculated to minimize the cost function, which enables the predicted output be as close as possible to the desired future output. The first two steps, shown in figure (2), are performed open loop to minimize the error $e(t)$, between the projected output and the reference input (set point). The loop is then closed by applying the calculated control signal to the system [12].
The DMC scheme can be seen in Figure (3) [5].

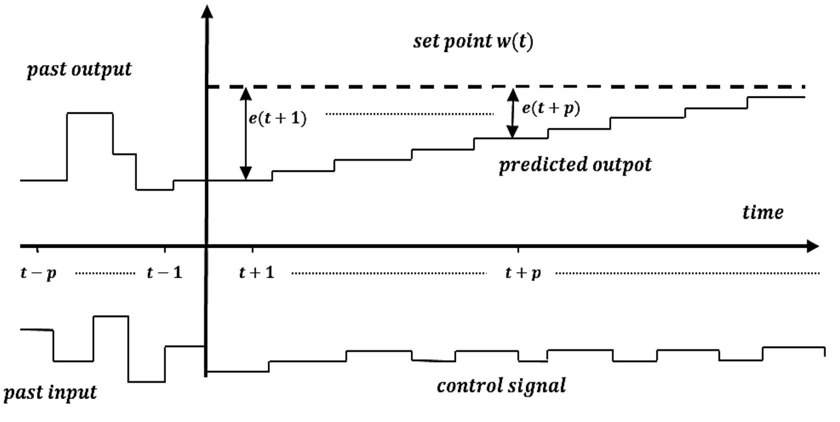

Figure (2): Basic DMC steps.

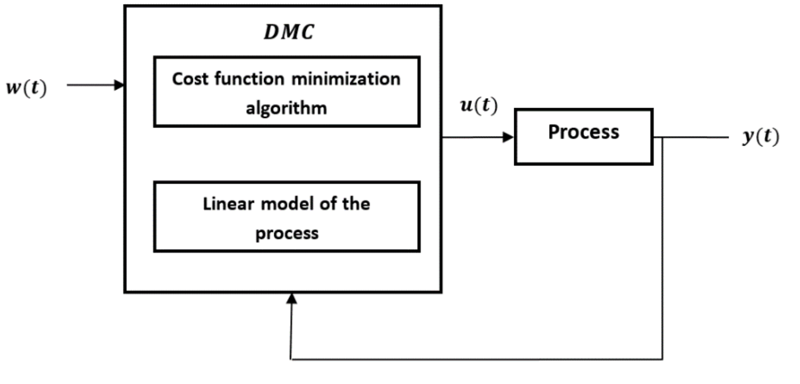

Figure (3): Basic structure of DMC.

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4- Formulation of Dynamic Matrix Control

The methodology proposed of DMC implemented using a step response model (dynamic response) of SISO plant; therefore, the procedure to obtain the predictions is as follows:

The step response model can be defined as:

$$y(t) = \sum_{i=1}^{\infty} g_i \, \Delta u(t-i) \tag{2}$$

Where, $u(t)$ and $y(t)$ are the control and output sequence of the plant and g_i is a sampled output values [5], [10], [11].

The predicted values (future output) well be:

$$\hat{y}(t+k/t) = \sum_{i=1}^{k} g_i \, \Delta u(t+k-i) + f(t+k) \tag{3}$$

Where $f(t+k)$ is the free response of the system, given by:

$$f(t+k) = y_m(t) + \sum_{i=1}^{N} (g_{k+i} - g_i) + \Delta u(t-i) \tag{4}$$

For stable process, the output coefficients are constant values after N sampling periods, therefor the free response can be written as:

$$f(t+k) = y_m(t) + \sum_{i=1}^{N} (g_{k+i} - g_i) + \Delta u(t-i) \tag{5}$$

The DMC algorithm consists of applying a control sequence that minimizes a multistage cost function of the form:

$$J = \sum_{j=1}^{N} [\hat{y}(t+j/t) - w(t+j)]^2 + \sum_{j=1}^{m} \lambda \, [\triangle \, u(t+j-1)]^2 \tag{6}$$

Where, $\hat{y}(t+j/t)$ is an optimum j-step ahead prediction of the system output on data up to time t, N maximum costing horizon, m is the control

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horizon, λ is a move suppression factor, and $w(t+j)$ is the future reference trajectory (set-point), which can be considered to be constant.

The objective of DMC is to compute the future control sequence $u(t)$, $u(t+1)\cdots$ in such a way that the future plant output $y(t + j)$ is driven close to $w(t + j)$, this is accomplished by minimizing J. [4], [5], [11].

To solve the DMC problem the set of control signals $u(t)$, $u(t+1)\cdots, u(t+N)$ has to be obtained in order to optimize cost function. N Should be as large when the plant dynamics is sufficiently represented (i.e., as large when the effect of the current control increment is included) [4], [5], [10].

Applying the prediction model described in equation (3) yields,

$$\hat{y}(t+1/t) = G_1(z^{-1})\Delta u(t) + F_1(z^{-1})$$

$$\hat{y}(t+2/t) = G_2(z^{-1})\Delta u(t+1) + F_2(z^{-1})$$

$$\vdots$$

$$\hat{y}(t+N/t) = G_N(z^{-1})\Delta u(t+N-1) + F_N(z^{-1})$$

which, can be written as:

$$\mathrm{Y} = \mathrm{GU} + \mathrm{F} \tag{7}$$

Where:

$$\mathrm{Y} = \begin{bmatrix} \hat{y}(t+1/t) \\ \hat{y}(t+2/t) \\ \vdots \\ \hat{y}(t+N/t) \end{bmatrix} \qquad \mathrm{U} = \begin{bmatrix} \Delta u(t) \\ \Delta u(t+1) \\ \vdots \\ \Delta u(t+N-1) \end{bmatrix}$$

$$(N \times N)\ matrix.\mathrm{G} = \begin{bmatrix} g_1 & 0 & \cdots & 0 \\ g_2 & g_1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ g_N & g_{N-1} & \cdots & g_1 \end{bmatrix}$$

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$$\mathrm{F}(z^{-1}) = \begin{bmatrix} F_1(z^{-1}) \\ F_2(z^{-1}) \\ \vdots \\ F_N(z^{-1}) \end{bmatrix}$$

If a unit step is applied the input at time t; that is

$$\Delta u(t) = 1, \qquad \Delta u(t+1) = 0, \cdots, \Delta u(t+N-1) = 0$$

The expected output sequence $[\hat{y}(t+1), \hat{y}(t+1), \cdots, \hat{y}(t+1)]^{\mathrm{T}}$is equal to the first column of matrix G. That is, the first column of matrix G can be calculated as the step response of the plant when a unit step is applied to the manipulated variable [4], [5].
According (5), the free response term can be calculated recursively by:

$$f_{j+1} = f_j + \sum_{i=1}^{N} (g_{j+i} - g_i) + \Delta u(t-i) \tag{8}$$

With $f_0 = y(t)$.
By substitute equation (7) into (6), the cost function can be written in the vector form,

$$J = (\mathrm{GU} + f - \mathrm{W})^{\mathrm{T}}(\mathrm{GU} + f - \mathrm{W}) + \lambda \mathrm{U}^{\mathrm{T}}\mathrm{U} \tag{9}$$

where,

$$\mathrm{W} = [w(t+1) \ \ w(t+2) \cdots w(t+N)]^{\mathrm{T}}$$

Equation (9) can be written as:

$$J = 0.5\ \mathrm{U}^{\mathrm{T}}\mathrm{HU} + \mathrm{b}^{\mathrm{T}}\mathrm{U} + f_0 \tag{10}$$

where,

$$\mathrm{H} = 2\ (\mathrm{G}^{\mathrm{T}}\mathrm{G} + \lambda \mathrm{I})$$
$$\mathrm{b}^{\mathrm{T}} = 2\ (f - \mathrm{W})^{\mathrm{T}}\mathrm{G}$$
$$f_0 = (f - \mathrm{W})^{\mathrm{T}}(f - \mathrm{W})$$

The minimum of J, assuming there are no constraints on the control signals, can be found by making the gradient of J equal to zero, which leads to the corresponding control law as below:

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$$U = -H^{-1}b = (G^TG + \lambda I)^{-1}G^T(W - f) \qquad (11)$$

Notice that the control signal that is actually sent to the process is the first element of the vector U, which is given by:

$$\Delta u(t) = K(W - f) \qquad (12)$$

Where K is the first row of the matrix $(G^TG + \lambda I)^{-1}G^T$.
So, according to the previous discussions the DMC control law could be illustrated as following in Figure (4) [4], [5].

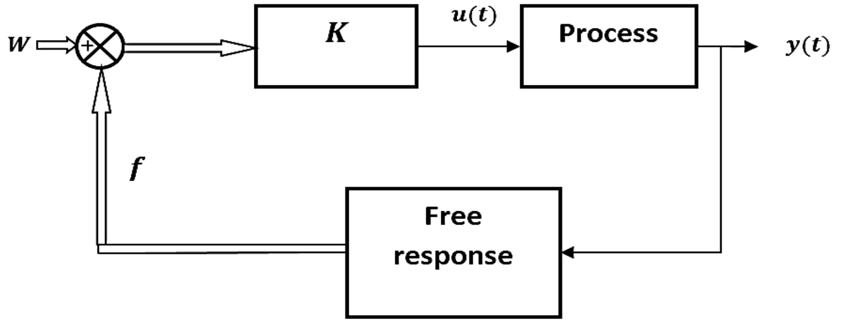

Figure (4): DMC control law.

5- The DMC Controller Design of SRM System

To design the DMC controller for the SRM system described in [7], we first obtain the mathematical form of the system in the discrete SISO form. This discrete equivalence can be easily obtained by discretizing the continuous time transfer function of the SRM system. This can be produced as follows:

$$y(t) = 0.006985\, y(t-1) + 10.56\, u(t-1)$$

By applying a step input to the SRM, dynamic matrix coefficients g_i can be obtained from the step response shown in figure (5), it can be seen in the table (1).

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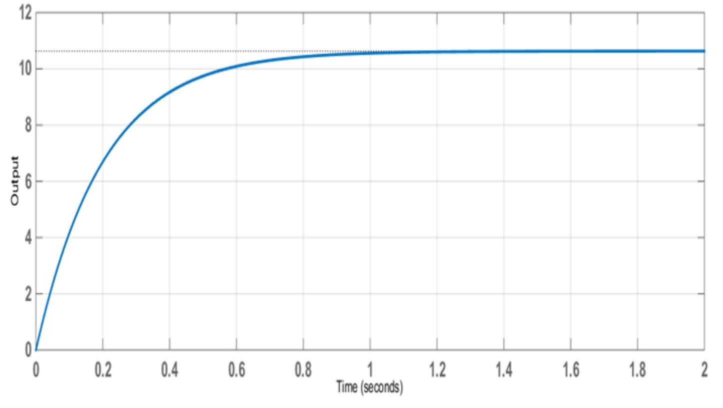

Figure (5): Step response of the open-loop SRM system.

Table (1): Dynamic matrix coefficients g_i.

g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}
0	0.4785	0.9354	1.3717	1.7884	2.1864	2.5665	2.9294	3.2760	3.6070
g_{11}	g_{12}	g_{13}	g_{14}	g_{15}	g_{16}	g_{17}	g_{18}	g_{19}	g_{20}
3.9231	4.2250	4.5133	4.7886	5.0516	5.3026	5.5424	5.7714	5.9901	6.1990
g_{21}	g_{22}	g_{23}	g_{24}	g_{25}	g_{26}	g_{27}	g_{28}	g_{29}	g_{30}
6.3984	6.5889	6.7708	6.9445	7.1104	7.2689	7.4202	7.5647	7.7026	7.8344
g_{31}	g_{32}	g_{33}	g_{34}	g_{35}	g_{36}	g_{37}	g_{38}	g_{39}	g_{40}
7.9603	8.0805	8.1952	8.3048	8.4095	8.5095	8.6049	8.6961	8.7832	8.8663

Depending on the DMC algorithm and the SRM mathematical model, which was developed and discussed in [7], the incremental program was built to calculate the desired control signal. This incremental program designed and implemented in MATLAB environment.

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Based on the resulting dynamic matrix coefficients, we can calculate the dynamic matrix G as follows:

$$G = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.4785 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.9354 & 0.4785 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.3717 & 0.9354 & 0.4785 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.7884 & 1.3717 & 0.9354 & 0.4785 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2.1864 & 1.7884 & 1.3717 & 0.9354 & 0.4785 & 0 & 0 & 0 & 0 & 0 \\ 2.5665 & 2.1864 & 1.7884 & 1.3717 & 0.9354 & 0.4785 & 0 & 0 & 0 & 0 \\ 2.9294 & 2.5665 & 2.1864 & 1.7884 & 1.3717 & 0.9354 & 0.4785 & 0 & 0 & 0 \\ 3.2760 & 2.9294 & 2.5665 & 2.1864 & 1.7884 & 1.3717 & 0.9354 & 0.4785 & 0 & 0 \\ 3.6070 & 3.2760 & 2.9294 & 2.5665 & 2.1864 & 1.7884 & 1.3717 & 0.9354 & 0.4785 & 0 \end{bmatrix}$$

Because only $\triangle u(t)$ is needed for the calculations, only the first row of the matrix $[(G^T G + \lambda I)^{-1} G^T]$ (or gain vector K) is used to calculate the control signal, and if the weighting factor λ is equal to one, then:

K = [0 0.1826 0.1952 0.1423 0.0811 0.0350 0.0079 -0.0050 -0.0098 -0.0117].

Using the gain vector K, set point and the free response polynomials, the steps of the prepared program will drive the system's output via the control signal to the optimal response.

Figure (6) shows the response of the SRM system with DMC controller.

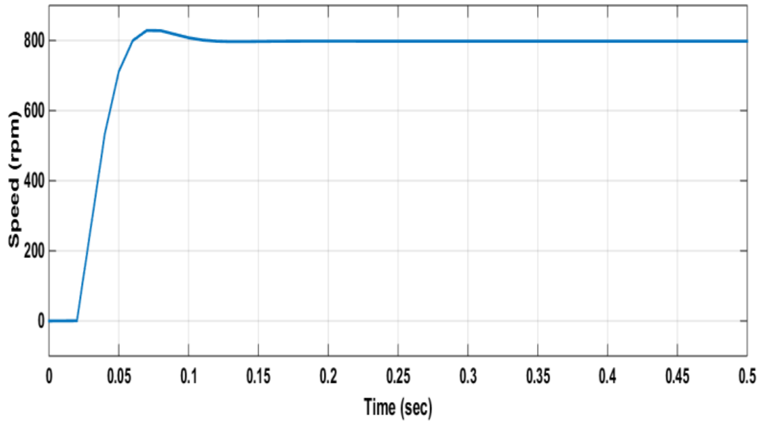

Figure (6): The response of the SRM system with DMC controller

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6- The selection of the Weighting Factor λ

In order to determine the effect of the change in the value of λ on the DMC controller as well as the response of the SRM system, we changed its values to get the best response of the system. It can be seen from figure (7) that the optimal response of the system is at λ=1.

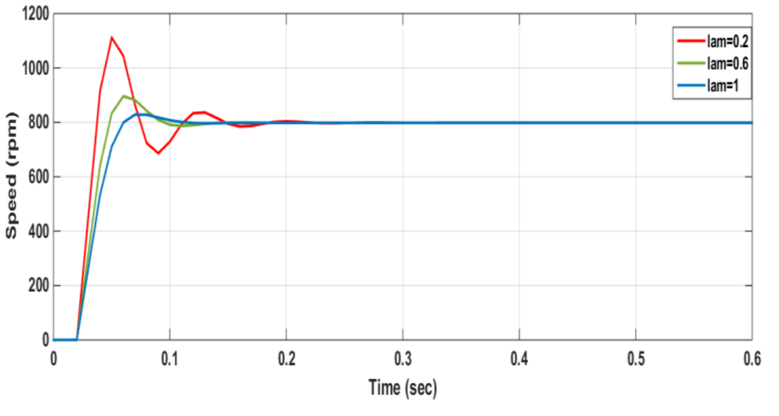

Figure (7): The response of the SRM system with DMC controller and different values of λ.

7- The PI Controller

In the study, we mentioned earlier in reference [7], the researcher designed a traditional PI controller using two methods: the classic (PI) method, and anti-reset windup (PI-AW) method, and we adopted their design in our study, in order to avoid the excessive and undesirable lengthening in such researches.

The following table shows the PI parameters for poth designs:

Table (2): PI and PI-AW parameters.

	k_p	K_i
PI	1.4	35.33
PI-AW	1.4	)35.33/(S + 35.33

In the aforementioned research [7], the researchers concluded that neither of the PI and PI-AW methods reached the design requirement of settling

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time, which is 0.1 sec. Therefore, they recommended a more precise method for describing the SRM model as well as controlling the required constraints.

For further illustration, table (3) shows a comparison between the design requirements as well as simulation values obtained for the SRM system with both controllers. Through these results, clearly indicate that the system with the DMC controller is faster response and more closed to the requirements.

Table (3): Summary of results using of the linear DMC/PI/PI-AW controllers.

	DMC	PI	PI-AW	Design requirements
Settling time (sec)	0.092	0.65	0.21	0.1
Over shoot (%)	3.575	18.75	1.25	5%
Steady state error	0.0125	1.25	0	0.1%

8- Discussions of the Results

In the normal case (without the effect of the uncertainty such as disturbance and noise), we noticed that the response time of the SRM system with PI and PI-AW controllers was not close to the design requirements for settling time, while the DMC are fastest than PI and PI-AW controllers, the DMC had (0.092 sec) settling time and it’s the range of required response.

The steady state errors without introducing any disturbances are (0.0125 rpm) with DMC, (0 rpm) with PI-AW and (1.25 rpm) with PI controller. From these results, we note that the steady state error with DMC and PI-

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AW does not exceed (0.1%). In fact, the system response had an overshoot on the response with poth controllers equal to (18.75%) with PI, (1.25%) with PI-AW and (3.575%) with DMC controller while it should be less than 5% in the requirements.

9- Conclusion

This research presents a successful application of the dynamic matrix controller, which controls the speed of the linear Switched Reluctance Machine model. This controller provides optimal primary control input necessary for tracking a certain reference speed trajectory within a permissible value. The DMC method is mainly based on the mathematical model of the system to predict its future output. This is used to minimize the system error so that the desired control signal is achieved. In addition, the DMC algorithm implemented and applied to the plant. The presented DMC controller has perfect features; such as fast response and accurate tracking of a desired set point. Based on the study it has concluded that, the DMC controller offers a better response than the classical PI control design.

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