CHAPTER 5

DIRECT MODEL REFERENCE ADAPTIVE INTERNAL MODEL CONTROLLERS FOR VOLTAGE SAG RIDE THROUGH

5.1 GENERAL

Renewable energy sources are considered as green energy technology sources in the world because of its low greenhouse gas emission. The draft report of the expert committee on Integrated Energy Policy Committee (2005) said “to deliver a sustained growth of 8% through 2031, India would, in the very least, need to grow its primary energy supply by five to seven times of today’s consumption”. The population curve may well level off in the middle of this century; but the consumption curve will keep on going up because we have well over two billion people in India and China alone who want to consume more power.

Wind power is the fastest-growing source of electric power generation with minimal environmental impact. Controller is another main part of the wind farms to improve the state of art performance. In recent years, robust controllers are gaining importance to improve the system performance by reducing the maintenance and operational cost.

The principal of model reference adaptive control strategy is used to design the adaptive controller that works on the principle of adjusting the controller parameters so that the output of the actual plant tracks the output of a reference model having the same reference input.
The current controller can be better understood by assuming that the DC bus voltage remains constant (that is, by assuming the system lossless). With this assumption, once the current reference has been generated from the load current, the problem reduces to making the inverter deliver the same at the PCC, with the help of the current controller. This means that the controller along with the inverter should resemble an all pass filter. However, in reality, the controller-inverter setup cannot resemble an all pass system. This means that the inverter is incapable of following any continuous current reference directly (as it would require the inverter to be able to produce a continuous voltage at its output) (Arun karuppaswamy 2007).

Once a disturbance (e.g. transient voltage dip) occurs on the motor, current, terminal voltage and synchronous torque developed will change and the motor may lose stability. Control of the motor to bring back the system to its stable operating point is an essential requirement. Modal control, which is an alternative to optimal control for linear systems, is attractive from the classical control designer's point of view. The algorithm for designing the modal control is computationally attractive compared to optimal control algorithm (Suryanarayana Sarma 1978) and various other control techniques are investigated in this thesis.

The paper discusses the use of an adaptive Maximum Power Point Tracking (MPPT) strategy to implement an efficiency maximization loop in parallel with the regular maximum tip-speed-ratio tracker, without the measurement of mechanical quantities. The overall power output of the generation system is increased with a minimal increase in controller cost (Rene Spee et al 1994).
5.2 DIRECT MODEL REFERENCE ADAPTIVE INTERNAL MODEL CONTROLLER

This controller is also known as mixed scheme of supervision and control. It mainly consists of a reference model in parallel, which adjusts to the desired response, if deviations of the temporal response from the expected trajectory are observed. A comparison between the output of the model used to impose a determined frequency response at selected point and the real response is done; if deviations are detected, the desired frequency response is modified according to a certain adaptation law. In the mentioned case, a simple constant has been used, but this scheme can utilize any of the classical design Model Reference Adaptive Control (MRAC) criteria, such as MIT Rule (Eduardo F. Camacho et al. 1997).

In model reference algorithms, a model, which the designer chooses, is made to specify the dynamics of the controlled system. The selection of the model is limited only in that the speed of the dynamics of the model should not greatly exceed the dynamics of the system under control; otherwise large control efforts might be required. An error signal is generated from the difference between the outputs of the model and plant. The model is driven by the reference input and the controller, which is adjusted by the error, drives the plant. Gains are modified within the controller such that the error is reduced. Adaptation stops when the error reaches zero since the plant's outputs are now tracking those of the model. Thus, the MRAC has forced the plant to behave like the model (Eric Unkauf & David Torrey 1995).

According to hyperstability theory, stable behavior of adaptive system could be achieved if reference model has the same order as adjustable system and if all state variables are used (Cmosija, P et al. 2002). For ensuring the fast-acting tracking performance, command generator tracker based model output following control method is discussed (Yuguo Chen
et al 2011). Raghav Khanna et al (2014) focused mostly on the design of the MRAC algorithm, which compensated the under damped characteristics of the power conversion system.

5.2.1 Reference Model

Reference model is used to give an idyllic response of the adaptive control system to the reference input. The reference model is a component of the adaptive controller responsible for setting the desired closed-loop dynamics. Notice that such dynamics are the target dynamics regardless of the uncertainty/failure that may occur on the plant. The reference model assumed is prescribed by the linear closed-loop system corresponding to the nominal controller (Luis G. Crespo et al 2010). A similar approach is taken in this controller.

A first order reference model is considered for a first order plant and this model is used to cater the desired behaviour of the closed loop system. Reference model design procedure given by the Ioannou & Sun 1996 is considered below.

Reference model assumptions

1. \( R_m(s) \) is monic Hurwitz polynomials

2. The relative degree is the same as that of plant model

The transfer function of the reference model given by

\[
R_m(s) = \frac{1}{(\phi s)^n + \lambda_n}
\]

\( ((\phi s)^n + \lambda_n) \) is a factor of \( \Lambda(s) \)
\( \Lambda(s) \) is an arbitrary monic Hurwitz polynomial of degree \( n-1 \)

(i.e.,) \( \Lambda(s) = \left( (\phi s)^{n} + \lambda_{0} \right) \Lambda_{q}(s) \) \hspace{1cm} (5.2)

\[ \Lambda_{q}(s) = s^{n-1} + q_{n-2}s^{n-2} + \cdots + q_{1}s + 1 \] \hspace{1cm} (5.3)

### 5.2.2 Adjustment Mechanism using MIT Rule

MIT rule is otherwise called sensitivity approach, and straightforward gradient approach. MIT rule based adjustment mechanism will not give stable closed loop system and the performance of the system is not consistent. Normally small gain is used in MIT rule for better performance, so it yields slow response (Mareels & Ydstie 1989). Figure 5.1 shows the general direct model reference adaptive IMC diagram with MIT rule.

The difference between the plant output and the reference model output is error in the system i.e \( e(s) \). The MRAS attempt to adjust the parameters so that the correlation between the error and the sensitivity derivative becomes zero. Note that the adaptive controller will react to any mismatch between the dynamics of the plant and the dynamics of the reference model regardless of its origin. In order to prevent these mismatches from triggering adaptation, the adaptive rate is driven to zero. The adaptive controller will only react to the parametric uncertainties it was designed for.

\[ e(s) = y(s) - y_{m}(s) \geq 0, \text{ is driven to zero} \] \hspace{1cm} (5.4)

This method is driven by the idea of minimizing the square of the prediction error. From this error a cost function of theta \( J(\theta) \) can be formed. \( J \) is given as a function of theta, with theta being the parameter that will be adapted inside the controller. The cost function is,
\begin{equation}
J(\theta) = -\frac{1}{2}e^2(\theta) \tag{5.5}
\end{equation}

To find out how to update the parameter \( \theta \), an equation needs to be formed for the change in \( \theta \). If the goal is to minimize this cost related to the error, it is sensible to move in the direction of the negative gradient of \( J \). This change in \( J \) is assumed to be proportional to the change in \( \theta \). Thus, the derivative of \( \theta \) is equal to the negative change in \( J \). The result for the cost function chosen above is (Coman Adrian et al 2008).

\begin{equation}
\frac{d\theta}{dt} = -\gamma e \frac{\delta e}{\delta \theta} \tag{5.6}
\end{equation}

Where \( \theta_0 \) is adjustable parameter vector, \( \gamma \) is the tuning rate to determine the convergence speed and \( \frac{\delta e}{\delta \theta} \) is the sensitivity derivative. The rate of change of parameter should be made proportional to the product of error and the model output (Karl John Astrom 1987).

This relationship between the change in \( \theta \) and the cost function is known as the MIT rule. The MIT rule is central to adaptive nature of the controller. Note the term pointed out in the equation above labeled "sensitivity derivative". This term is the partial derivative of the error with respect to \( \theta \). This determines how the parameter \( \theta \) will be updated. The MIT rule based adjustment mechanism is denoted as \( A_m \). This mechanism system attempt to adjust the parameter in the closed loop system

\begin{equation}
\theta_0 = -\frac{\gamma}{s}e(s)\tilde{y}(s) \gamma > 0 \tag{5.7}
\end{equation}

Where \( \gamma \) is adaptation gain (smaller value will give better result), integral action of this adjustment mechanism is used to eliminate the steady state error. Gain in the feedback loop increases the system response and
stability. In the model reference approach the stability of the system is improved indirectly (Li & Lau et al. 1988).

Figure 5.1 Direct model reference adaptive IMC diagram

5.2.3 Comparison Results of IMC with Direct Model Reference Adaptive IMC

Figure 5.2 shows the comparison of stator flux in the IMC and DMRIMC (Amuthan & Singh 2009). At the end of voltage sag stator flux have some oscillations before a constant value is reached. It is reduced in the DMRAIMC controller. The rise in stator flux to overcome the voltage sag at the end time is slightly high in the DMRAIMC due to adaptive control adjustment mechanism.
Figure 5.2 Comparison of stator flux with IMC and direct model reference adaptive IMC

Figure 5.3 shows the comparison of torque in IMC with direct model reference adaptive IMC. The torque spikes in voltage sag initial time and end time is reduced using the DMRAIMC controller compared to IMC controller. The voltage sag can result in large torque fluctuations in the variable speed wind turbines.

Figure 5.3 Comparison of torque in IMC with direct model reference adaptive IMC
Figure 5.4 shows the comparison of speed in IMC with direct model reference adaptive IMC. The VSRT control will result in an increase of rotational speed, as the electrical torque will decrease, because of the reduction in electrical power. The rotational speed will increase depends on the inertia of the turbine and the pitch speed. The relation between power, inertia and rotational speed is given in the equation 3.26. The overspeed is minimized using DMRIMC compared to IMC controller.

![Comparison of speed in IMC with direct model reference adaptive IMC](image)

**Figure 5.4  Comparison of speed in IMC with direct model reference adaptive IMC**

Figure 5.5 shows the comparison of stator active power in IMC with direct model reference adaptive IMC. Active power reductions are proportional to the voltage drop. At the time of fault clearing, the stator active power oscillates twice its original value. The initial fault oscillation is under control in the DMRAIMC.
5.2.4 Direct Model Reference Adaptive IMC with FuzzyMIT Adjustment Mechanism

An optimum response of the conventional fuzzy controller can be expected only for a limited range of inputs, because the controller has been dimensioned and formulated in a straightforward way on the basis of the basic operational characteristics of the plant.

Here, the constant gain, which is used in the MIT rule, is replaced by the fuzzy rules, which make the gain variable, i.e. the system is now made into an adaptive gain system. The gain is now controlled online according to the current states of the controlled process. Both error and error change are required to evaluate the control input; the fuzzy controller has more adaptive capability. Actually, the fuzzy adjustment mechanism monitors the system and adjusts the gain to improve the performance. Since the gain is being adjusted (variable), different sets of fuzzy control rules are used, and hence the fuzzy controller can operate for a large range of inputs. To prevent instability problems, the gain for the fuzzy adjustment mechanism is kept as
low as possible so that the system remains stable within the range of
operation. However, low gain increases the response time of the system; it is
being avoided in our work by varying the system gain, to increase the
adaptability of the controller.

Figure 5.6 shows the general Direct Model Reference Adaptive
IMC with FuzzyMIT adjustment mechanism. The equation for the fuzzy
adjustment mechanism FuzzyMIT is given in 4.20.

Figure 5.6 Direct model reference adaptive IMC with FuzzyMIT
adjustment mechanism
5.2.5 Comparison Results of Direct Model Reference Adaptive IMC with MIT Rule and FuzzyMIT Rule

Figure 5.7 shows that the stator flux due to 50% sag stator voltage is introduced for this analysis. There will be high oscillations of the stator and rotor currents due to the dc component of the stator flux. Rotor current controller is used to compensate for this dc component of the stator flux. The transient variations are negligible in MIT rule and FuzzyMIT adjustment mechanisms.

![Graph showing stator flux during voltage sag in DFIG using direct model reference adaptive IMC](image)

**Figure 5.7** Stator flux during voltage sag in DFIG using direct model reference adaptive IMC

Figure 5.8 shows that the rotor flux p.u is high in MIT rule but in FuzzyMIT rule, the rotor flux is under control. The rotor flux also settled quickly below the per unit value, which shows reliable operation of DFIG in FuzzyMIT adjustment mechanism.
Figure 5.8  Rotor flux during voltage sag in DFIG using direct model reference adaptive IMC

During voltage sags, the currents will be extremely high because, the inverter will not response fast to counteract the high Electro Motive Force (EMF) induced in the rotor. In this situation, the RSC may be destroyed. Figure 5.9 shows that the rotor current is very high in the initial fault time and the fault clearance time, but in FuzzyMIT the rotor current quickly reaches the p.u value compared to MIT rule adjustment mechanism. Rotor current is mainly used to generate active power but during fault, it is used to generate reactive power to support terminal voltage. It is also mandatory to limit the rotor current to avoid the damage of the RSC. The rotor current after fault clearance returns to its steady state value without any further oscillations.
Figure 5.9  Rotor current during voltage sag in DFIG using direct model reference adaptive IMC

Figure 5.10 shows that due to sudden drop in stator current during voltage sag the DC component present in the stator current, appears as AC in the rotor current, and the converter injects steady state rotor current. Thus, large peak in rotor current p.u is observed during initial fault and fault clearance. This is one of the severe problems in FRT.

Figure 5.10  Stator current during voltage sag in DFIG using direct model reference adaptive IMC
Figure 5.11 shows that after the fault clearance, the torque response is high and it oscillates like the initial transient of the machine and it is settled after 3s. The torque peak is high in the MIT rule adjustment mechanism during initial fault and fault clearance time compared to FuzzyMIT adjustment mechanism.

Figure 5.11 Torque of DFIG during voltage sag using direct model reference adaptive IMC

Figure 5.12 shows that the rotor active power supply is high in the FuzzyMIT adjustment mechanism and large transient occurs in FuzzyMIT adjustment mechanism during initial fault and the fault clearance time.

Figure 5.12 Rotor active power of DFIG during voltage sag using direct model reference adaptive IMC
After the grid voltage recovers the original state, the DFIG can supply maximum active power captured from the wind. When the voltage dips remains for a longer time, the generator is required to supply reactive power to the grid voltage recovery. Figure 5.13 shows that the stator active power peak is very high during clearance of fault and it is high in the FuzzyMIT adjustment mechanism. The stator active power supply remains constant after 17s.

![Figure 5.13 Stator active power of DFIG during voltage sag using direct model reference adaptive IMC](image)

Figure 5.13  Stator active power of DFIG during voltage sag using direct model reference adaptive IMC

Figure 5.14 shows that the controller is used to control the rotor currents and to supply reactive power. If fault occurs, the voltage is decreased and consequently the reactive power supply is decreased after a minor interval of transient.

At initial fault time, the reactive power supply is increased and the DFIG remains connected to the grid. Otherwise, the grid loses its synchronism. Also, the rotor reactive power supply is high in the fuzzy rule based adjustment mechanism. From the simulation, MIT rule adjustment mechanism rotor reactive power operation is smooth and the transients, due to
reactive power generation, are low. The FuzzyMIT adjustment mechanism supplies approximately 0.01p.u reactive power during voltage sag and the reactive power reach the equilibrium shortly, which is approximately in 1.5s after clearing the fault. By using the fuzzy rules adjustment mechanism the reactive power generation is improved and torque ripples are minimized significantly.

![Graph showing rotor reactive power during voltage sag using direct model reference adaptive IMC.](image)

**Figure 5.14** Rotor reactive power during voltage sag using direct model reference adaptive IMC

The wind turbine can supply reactive power during the dip, as is demanded by grid connection requirements for wind turbines. From figure 5.15 it is clear that, large reactive power peak occurs during the clearance of faults after the voltage sag. This peak is caused by demagnetization of the machine. These problems lead to the instability of DFIG control. This instability problem can be limited, using power electronic converters in the DFIG control and DFIG will resume supply power to grid after voltage sag.
Stator reactive power supply is high (1.15 p.u) in the FuzzyMIT adjustment mechanism.

Figure 5.15  Stator reactive power during voltage sag using direct model reference adaptive IMC

During the voltage sag, the rotor currents reach high values when compared with the value before the sag. These high values are caused by the natural stator flux that induces high rotor voltages. Figure 5.16 shows that the rotor voltage is oscillating slightly above 0.01p.u due to drop in stator power. Also due to higher rotor speed during fault, the rotor voltage increases.
From figure 5.17 it is clear that due to the large inertia of the wind turbine rotor, with increase in rotational speed, the limited active power supplied to the grid is reduced during voltage dip and this power is instantaneously less than the mechanical power of the DFIG. Hence, the rotor speed of the generator increases. Speed response is increased slightly in rule-based adjustment mechanism.

Figure 5.17 DFIG rotor speed during voltage sag using direct model reference adaptive IMC

Figure 5.18 shows that for different wind speeds like 6.45 m/s, 9.45 m/s and 12.45 m/s kept in the simulation and the rotor speed is observed, in
the lower wind speed. The rotor speed is within the per unit value and in the higher wind speed the rotor is above the per unit value. The rotor speed increases gradually from low to high speed for change in wind speed from lower to higher speed. The machine cuts in a speed between 3.5 – 4 m/s of wind speed and gives full load output at a speed around 12.5 m/s. The generation remains constant up to 20 or 25 m/s keeping the output speed constant. In the cut out wind speed the machine stops the generation.

![Performance of DFIG rotor speed with variable wind speed during voltage sag](image)

**Figure 5.18** Performance of DFIG rotor speed with variable wind speed during voltage sag

Figure 5.19 shows that the torque is inversely proportional to the rotor speed. In high-speed wind, torque is low and in low speed wind, the torque is high. During voltage sag generator torque falls below the level of the turbine torque and it accelerates the rotor speed; also increases the rotor angle and subsequently increases the load torque of the generator. Under normal operating conditions, the active power is generated based on wind speed and wind turbine characteristics.
Figure 5.19 Performance of DFIG torque with variable wind speed during voltage sag

Figure 5.20 shows that as the wind speed increases, the rotor active power also increases. FuzzyMIT adjustment mechanism injects power that is more active during voltage sag, so the transient is high.

Figure 5.20 Performance of DFIG rotor active power with variable wind speed during voltage sag.
Stator active power increased to above 1 p.u. it can be seen that the system becomes unstable with an increasing amplitude. After fault clearing the stator active put back the system into a stable operating condition. Figure 5.21 shows that the stator active power decreases when the wind speed increases. Active power is high in FuzzyMIT compared to MIT rule.

Figure 5.21  Performance of DFIG stator active power with variable wind speed during voltage sag.

Figure 5.22 shows that the stator reactive power injection is high when the wind speed increases. Reactive power injection is above the per unit value in the FuzzyMIT and it is within the per unit value in the MIT rule.

Figure 5.22  Performance of DFIG stator reactive power with variable wind speed during voltage sag.
Figure 5.23 shows that the rotor reactive power injection is increased when the wind speed is high in the FuzzyMIT and the transient is high. The generator supplies reactive power to the grid depends on the circuit time constants.

![Figure 5.23 Performance of DFIG rotor reactive power with variable wind speed during voltage sag](image)

**5.2.6 Direct Model Reference Adaptive IMC with AnfisMIT**

Figure 5.24 shows the general direct model reference adaptive IMC with AnfisMIT adjustment mechanism. In this controller, the adjustment mechanism gain is varied using ANFIS. The equation for AnfisMIT adjustment mechanism is given in 4.23. The ANFIS based adjustment mechanism can handle high gain without affecting the dynamic performance of the system. The instability problem due to high gain in the MIT rule adjustment mechanism is completely alleviated using the AnfisMIT based variable gain adjustment mechanism.
5.2.7 Comparison Results of Direct Model Reference Adaptive IMC with FuzzyMIT and AnfisMIT Rule

Figure 5.24 Direct model reference adaptive IMC with AnfisMIT adjustment mechanism

Figure 5.25 shows the stator flux during voltage sag. Stator flux is nearly the same in variable gain adjustment mechanism (FuzzyMIT) and linearly varying in adjustment mechanism (AnfisMIT). The transient response is minimized using the controller. In the beginning and end of the voltage sag, the transient response is high because protection circuit was not provided.
Figure 5.25 Stator flux using variable gain adjustment mechanisms

Figure 5.26 shows the rotor fluxes of the DFIG during voltage sag. In the AnfisMIT adjustment mechanism, the rotor flux is within the permitted per unit value and the sag duration is increased in the linearly varying adjustment mechanism.

Figure 5.26 Rotor flux using variable gain adjustment mechanisms
Figure 5.27 shows the stator current during voltage sag. The current per unit level is increased in the AnfisMIT adjustment mechanism, the initial current transient peak is reduced and final transient peak is slightly increased. The linearly varying adjustment mechanism quickly clears the voltage sag compared to FuzzyMIT. For stator currents, with variable gain adjustment mechanism further enhancement in current limitation will be achieved.

![Stator current using variable gain adjustment mechanisms](image)

**Figure 5.27 Stator current using variable gain adjustment mechanisms**

Figure 5.28 shows the rotor current during voltage sag. The maximum value the currents reach depends mainly on the depth of the voltage sag and the stator and rotor leakage inductance. The current level is increased in the AnfisMIT adjustment mechanism. Initial transient peak is reduced and the final transit limit is high in the AnfisMIT, nearly four times higher without protection circuit. After fault clearance, the current exhibits an inverse peak, where fault clearance normally results in transient components similar to that at fault initiation but with less severity.
Figure 5.28 Rotor current using variable gain adjustment mechanisms

Figure 5.29 shows the rotor active power. The rotor active power generation in the linearly varying adjustment mechanism increases in the initial and final voltage sag transient. The energy stored the rotor is temporarily increased during fault clearing time.

Figure 5.29 Rotor active power using variable gain adjustment mechanisms

Figure 5.30 shows the stator active power of DFIG during voltage sag. The real power outputted by the machine is small; hence, large amount of mechanical power provided by the turbine will be stored in the rotor inertia. As the controller response to the fault, the stator voltages vary. The machine is able to produce reactive power during the fault resulting in an increase in stator
The negative sign in the p.u. indicates that the active power is fed to the grid. The peak overshoot during fault is nearly two times in the final voltage sag.

![Graph showing stator active power using variable gain adjustment mechanisms](image)

**Figure 5.30** Stator active power using variable gain adjustment mechanisms

Figure 5.31 shows the stator reactive power. The reactive power varies proportionally with the voltage, and the actual reactive power absorption depends upon the power flow level. AnfisMIT adjustment mechanism produces high reactive power.

![Graph showing stator reactive power using variable gain adjustment mechanisms](image)

**Figure 5.31** Stator reactive power using variable gain adjustment mechanisms
Increasing the reactive power pulsation increases the imbalance of the stator current. During voltage sag, the active power drops and the generator supplies reactive power to the grid depending on the rotor circuit time constants as can be seen in figure 5.32. The improvement in the variable gain adjustment mechanism is shown in figure.

![Figure 5.32 Rotor reactive power using variable gain adjustment mechanisms](image)

In figure 5.33 shows that during voltage sag, the active power decreases and the rotor speed increases due to decrease in electromagnetic torque. During fault, the electromagnetic torque of DFIG is reduced to zero and the rotor accelerates. The rotor overspeed can be minimized using AnfisMIT.
Figure 5.33 DFIG rotor speed using variable gain adjustment mechanisms

Figure 5.34 shows the variation of rotor voltage for different adjustment mechanisms. The injection of reactive power to a node tends to raise the voltage level. The rotor voltage is increased in the AnfisMIT adjustment mechanism.

Figure 5.34 Rotor voltage using variable gain adjustment mechanisms

Torque varies inversely proportional to the rotor speed as seen from figure 5.35. The torque level is determined by the voltage and frequency. The torque level is minimized slightly in the AnfisMIT adjustment mechanism. It is important to note that the inverse peak after fault clearance has also been decreased.
Figure 5.35 Torque of DFIG using variable gain adjustment mechanisms

Figure 5.36 shows the stator fluxes of DFIG with various wind speed conditions. One can notice that the stator flux linkage depends on the stator voltage and the rotor current components; it decays exponentially with the stator time constant. As the wind speed increases, the stator flux level also increases.

Figure 5.36 Stator flux with various wind speed conditions in variable gain adjustment mechanisms
Figure 5.37 shows the rotor fluxes of DFIG with various wind speed conditions. The improved performance with wind speed increase is shown in figure.

![Rotor flux with various wind speed conditions in variable gain adjustment mechanisms](image)

**Figure 5.37** Rotor flux with various wind speed conditions in variable gain adjustment mechanisms

Figure 5.38 shows the rotor current of DFIG during voltage sag. As the wind speed increases, rotor current also increases and it is high in the linearly varying adjustment mechanism. The losses and current increases the power factor becomes low.

![Rotor current with various wind speed conditions in variable gain adjustment mechanisms](image)

**Figure 5.38** Rotor current with various wind speed conditions in variable gain adjustment mechanisms
Figure 5.39 shows the stator current during voltage sag in DFIG with various wind speed conditions. Stator current increases when the wind speed increases. Neglecting the magnetizing current the stator current is proportional to the rotor current. Therefore, the stator current is also increases with increased slip.

![Stator current with various wind speed conditions in variable gain adjustment mechanisms](image)

**Figure 5.39** Stator current with various wind speed conditions in variable gain adjustment mechanisms

Figure 5.40 shows the stator active power during voltage sag in DFIG with various wind speed conditions. The wind speed increases the power fed to the grid as shown in figure with negative sign.

![Stator active power with various wind speed conditions in variable gain adjustment mechanisms](image)

**Figure 5.40** Stator active power with various wind speed conditions in variable gain adjustment mechanisms
Figure 5.41 shows the rotor active power during voltage sag in DFIG with various wind speed conditions. The rotor active power increases when the wind speed increases.

![Rotor active power with various wind speed conditions](image1)

**Figure 5.41 Rotor active power with various wind speed conditions in variable gain adjustment mechanisms**

Figure 5.42 shows the rotor reactive power during voltage sag in DFIG with various wind speed conditions. Rotor reactive power generation increases when wind speed increases.

![Rotor reactive power with various wind speed conditions](image2)

**Figure 5.42 Rotor reactive power with various wind speed conditions in variable gain adjustment mechanisms**
Figure 5.43 shows the stator reactive power during voltage sag in DFIG with various wind speed conditions. The stator reactive power increases when the wind speed increases.

![Stator Reactive Power with Various Wind Speed Conditions](image)

**Figure 5.43** Stator reactive power with various wind speed conditions in variable gain adjustment mechanisms

Figure 5.44 shows the torque with various wind speed conditions. During the fault, the torque oscillation is less in the AnfisMIT adjustment mechanism. The rotor torque is decreased as wind speed increases.

![Torque with Various Wind Speed Conditions](image)

**Figure 5.44** Torque with various wind speed conditions in variable gain adjustment mechanisms
Figure 5.45 shows the rotor speed during voltage sag in DFIG with various wind speed. The rotor speed increases when the wind speed increases. In the case of an underdamped power system, any minor disturbance can cause the machine angle to oscillate around its steady-state value at the natural frequency of the total electromechanical system. The angle oscillation, of course, results in a corresponding power oscillation around the steady-state power transmitted. The lack of sufficient damping can be a major problem in some power systems and, in some cases; it may be the limiting factor for the transmittable power (Narain G.Hingorani & Laszlo Gyugyi 2000).

Figure 5.45  Rotor speed with various wind speed conditions in variable gain adjustment mechanisms

Figure 5.46 shows the rotor voltage with various wind speed. The rotor voltage variation is very small as the wind speed increases. The electric power transmitted must be increased to compensate for the excess mechanical input power.
Comparison of active power using variable gain adjustment mechanism is presented in the Table 5.1 and comparison of reactive power using variable gain adjustment mechanism is presented in the Table 5.2.

**Table 5.1 Comparison of Active Power FuzzyMIT and AnfisMIT adjustment mechanism**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>FuzzyMIT</th>
<th>AnfisMIT</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Rotor active power</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Very low</td>
<td>0.8%</td>
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<tr>
<td></td>
<td>Initial transient in rotor active power</td>
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<tr>
<td>2.</td>
<td>Very low</td>
<td>1.6%</td>
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<tr>
<td></td>
<td>Final transient in rotor active power</td>
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</tr>
<tr>
<td>3.</td>
<td>Very low</td>
<td>3.7%</td>
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<tr>
<td></td>
<td>Stator Active power</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>77%</td>
<td>77%</td>
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<tr>
<td></td>
<td>Initial transient in stator active power</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Above the p.u value</td>
<td>above the p.u value</td>
</tr>
<tr>
<td></td>
<td>Final transient in stator active power</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Above the p.u value</td>
<td>above the p.u value</td>
</tr>
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</table>
Table 5.2  Comparison of reactive power using FuzzyMIT and AnfisMIT adjustment mechanism

<table>
<thead>
<tr>
<th>S.No</th>
<th>FuzzyMIT</th>
<th>AnfisMIT</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Rotor reactive power</td>
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</tr>
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<td>0.17%</td>
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<tr>
<td>2.</td>
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<td>4.1%</td>
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<td></td>
<td>Final transient in Rotor reactive power</td>
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<tr>
<td>3.</td>
<td>Very low</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>stator reactive power</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>37.7%</td>
<td>80.6%</td>
</tr>
<tr>
<td></td>
<td>Initial transient in stator reactive power</td>
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</tr>
<tr>
<td>5.</td>
<td>Above p.u.value</td>
<td>Above p.u.value</td>
</tr>
<tr>
<td></td>
<td>Final transient in stator reactive power</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Above p.u.value</td>
<td>Above p.u.value</td>
</tr>
</tbody>
</table>

5.3 IMPROVED DIRECT MODEL REFERENCE ADAPTIVE INTERNAL MODEL CONTROLLER

Figure 5.47 shows the improved direct model reference adaptive IMC with MIT rule adjustment mechanism. The equation for MIT rule adjustment mechanism is given in 5.7. To improve the performance of the controller a dither signal is injected in the controller during fault.
Figure 5.47 Dither injected direct model reference adaptive IMC with MIT Rule adjustment mechanism

Figure 5.48 shows the improved direct model reference adaptive IMC with FuzzyMIT adjustment mechanism. The controller provides the appropriate control signal $u(s)$ to the process in order to maintain the process output $y(s)$ as close as possible to the desired output $y_m(s)$ specified by the reference model. The error $e(s)$ between the reference model and process outputs is used in the adaptor to adjust the controller parameters. The equation 4.20 provides the AnfisMIT adjustment mechanism. The system has the ordinary feedback loop also known as outer loop that includes the process and the controller, and another feedback loop usually called inner loop related to the adaptation of the controller parameters.
Figure 5.48 Improved direct model reference adaptive IMC with FuzzyMIT adjustment mechanism

Figure 5.49 shows the general direct model reference adaptive IMC with AnfisMIT adjustment mechanism. The equation for AnfisMIT adjustment mechanism is given in 4.23. The superimposed dither signal is given in figure 4.34. The design of nonlinear model reference adaptive controllers is limited for various reasons. These control algorithms are often complex, a solution does not always exist and as a result their analysis and design become difficult and time consuming procedures. Moreover, the complexity can also introduce a considerable amount of time required for their implementation. This imposes a serious constraint when the sample time is fast (Ioannis douratsos & J. barry gomm 2007).
Figure 5.49 Improved direct model reference adaptive IMC with AnfisMIT adjustment mechanism

5.3.1 Simulation Results of Improved Direct Model Reference Adaptive Internal Model Controllers

Figure 5.50 shows the stator flux variation in DFIG during voltage sag condition. It is observed that the stator flux is nearly the same in both variable gain (FuzzyMIT) and linearly varying (AnfisMIT) adjustment mechanisms. However, if the amplitude of the dither signal is increased then the flux level also will increase.
Figure 5.50  Stator flux during voltage sag in DFIG using improved direct model reference adaptive IMC

In figure 5.51, the rotor flux of the DFIG is within per unit value and has faster response, using AnfisMIT adjustment mechanism compared to other mechanisms. In addition, the adjustment mechanism along with dither injection further increases the flux sag.

Figure 5.51  Rotor flux during voltage sag in DFIG using improved direct model reference adaptive IMC
The stator current in DFIG is within per unit value during voltage sag and the final transit peak is also reduced using AnfisMIT adjustment mechanism as shown in figure 5.52. In addition, using dither injection increases the current level.

Figure 5.52  Stator current during voltage sag in DFIG using improved direct model reference adaptive IMC

Figure 5.53 shows the rotor current during voltage sag in DFIG. The initial transient peak of the rotor current is high and the final transient limit is reduced in the AnfisMIT adjustment mechanism, and it is nearly four times higher without protection circuit. Usage of dither injection has reduced the transient and the current level. It can be seen in the figure that the maximum rotor current increases with the size of the voltage sag.

Figure 5.53  Rotor current during voltage sag in DFIG using improved direct model reference adaptive IMC
Figure 5.54 shows the rotor active power in DFIG during voltage sag. The rotor active power generation is increased in the FuzzyMIT adjustment mechanism and the transient peak is reduced using the dither injection scheme. AnfisMIT gives better result in the graph and the transient peak is under control.

![Rotator active power diagram](image)

**Figure 5.54 Rotor active power during voltage sag in DFIG using improved direct model reference adaptive IMC**

Figure 5.55 shows the stator active power of DFIG during voltage sag. The negative sign in the per unit (p.u) indicates that the active power is fed to the grid. During fault condition, the peak overshoot is nearly two times in the final stage and using dither injection increases the stator active power.

![Stator active power diagram](image)

**Figure 5.55 Stator active power of DFIG during voltage sag using improved direct model reference adaptive IMC**
Figure 5.56 shows that the stator reactive power during voltage sag and the reactive power increase in the FuzzyMIT adjustment mechanism. The final transient peak is reduced in the AnfisMIT adjustment mechanism and usage of dither injection further increases the reactive power level.

![Stator reactive power during voltage sag using improved direct model reference adaptive IMC](image1)

**Figure 5.56** Stator reactive power during voltage sag using improved direct model reference adaptive IMC

Increasing the reactive power pulsation increases the unbalance of the stator current. Dither injection increases the rotor reactive power and as shown in figure 5.57, any increase in reactive power will result in corresponding increase in the initial and final transients during voltage sag. The dither injection further increases the reactive power transients.

![Rotor reactive power during voltage sag using improved direct model reference adaptive IMC](image2)

**Figure 5.57** Rotor reactive power during voltage sag using improved direct model reference adaptive IMC
During voltage sag, the rotor speed increases due to the mechanical power in spite of decrease in the active power. As shown in figure 5.58 use of dither injection still increases the rotor speed. Increase in rotor speed during voltage sag can be minimized using AnfisMIT.

![Figure 5.58 DFIG rotor speed during voltage sag using improved direct model reference adaptive IMC](image)

Figure 5.59 shows the rotor voltage during voltage sag in DFIG. Use of dither injection technique increases reactive power in the node, which in turn tends to raise the voltage level. The rotor voltage is increased in FuzzyMIT adjustment mechanism compared to other mechanisms. The dither injection further increases the voltage level.

![Figure 5.59 Rotor voltage during voltage sag using improved direct model reference adaptive IMC](image)
Torque is inversely proportional to the rotor speed and as shown in figure 5.60. The torque level is low in the AnfisMIT adjustment mechanism and the torque ripple is minimized using dither signal. The machine needs some time to build up its torque after the fault is cleared.

![Torque vs Time graph]

**Figure 5.60 Torque of DFIG during voltage sag using improved direct model reference adaptive IMC**

Comparison of active and reactive powers using fixed and variable gain adjustment mechanisms are presented in the Table 5.3 and 5.4.

**Table 5.3 Comparison of active power using fixed gain and variable gain adjustment mechanism**

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>MIT Rule</th>
<th>MIT Rule with Dither</th>
<th>FuzzyMIT with Dither</th>
<th>AnfisMIT with Dither</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rotor active power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>0.01%</td>
<td>0.01%</td>
<td>1.7%</td>
<td>0.8%</td>
</tr>
<tr>
<td></td>
<td>Initial transient in rotor active power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>0.8%</td>
<td>5.1%</td>
<td>9.4%</td>
<td>7.6%</td>
</tr>
<tr>
<td></td>
<td>Final transient in rotor active power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>0.4%</td>
<td>0.4%</td>
<td>5%</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>Stator Active power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>76%</td>
<td>76%</td>
<td>77%</td>
<td>77%</td>
</tr>
<tr>
<td></td>
<td>Initial transient in stator active power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>5.5%</td>
<td>5.5%</td>
<td>5.5%</td>
<td>5.5%</td>
</tr>
<tr>
<td></td>
<td>Final transient in stator active power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Above p.u.value</td>
<td>Upper bounds</td>
<td>Above p.u.value</td>
<td>Above p.u.value</td>
</tr>
</tbody>
</table>
Table 5.4  Comparison of reactive power using fixed gain and variable gain adjustment mechanism

<table>
<thead>
<tr>
<th>S.No</th>
<th>MIT Rule</th>
<th>MIT Rule with Dither</th>
<th>FuzzyMIT with Dither</th>
<th>AnfisMIT with Dither</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotor Reactive Power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>0.5%</td>
<td>0.5%</td>
<td>1%</td>
<td>0.6%</td>
</tr>
<tr>
<td></td>
<td>Initial transient in Rotor reactive power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>12%</td>
<td>12%</td>
<td>18%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Final transient in Rotor reactive power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>10%</td>
<td>10%</td>
<td>9%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>Stator reactive power</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>31%</td>
<td>31%</td>
<td>Above p.u.value</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>Initial transient in stator reactive power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>8%</td>
<td>8%</td>
<td>31%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>Final transient in stator reactive power</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Above p.u.value</td>
<td>Above p.u.value</td>
<td>Above p.u.value</td>
<td>Above p.u.value</td>
</tr>
</tbody>
</table>