It is well known that the rated reactive capability of an alternator as indicated by capability curves given by the manufacturer, is not entirely available both in lagging and leading power factor operation modes due to station constraints. The alleviation of these constraints requires frequent adjustment of generator transformer and auxiliary transformer taps. However in many utilities there is reluctance to operate the transformers on load taps due to reliability consideration. In this paper an optimisation methodology is proposed to select the optimised taps of generator transformer and auxiliary transformer so as to minimise this unavailability while satisfying station constraints over a range of loading and system voltages. Optimisation results for a typical 210 MW thermal generator have been obtained to demonstrate the potential of the algorithm.

2. INTRODUCTION:
The Synchronous generator with its controls is one of the most complex devices in a power system. For simplified analysis, the steady state operation of synchronous generator can be characterised by three variables, P (Active Power), Q (Reactive Power) and V (Generator terminal voltage). The graphical representation of a synchronous machine P & Q operating limits at a constant V is demonstrated by curve called Capability curve. Such curves are furnished by the generator manufacturer at the time of purchase and called GRC (Generator Rated Capability-Chart) and drawn as the net result of various internal constraints of the generator internal designs like armature and rotor current limits (on lagging side) and minimum excitation and stability limit etc (on leading side). These curves do not consider limitations due to power plant and power system operating conditions and other limiting factors[1, 2].

Adibi and Milanicz [1] have demonstrated that realisable generator reactive capability is generally much lesser than that indicated by GRC furnished by manufacturers, due to additional constraints imposed by Plant equipment during system voltage variation. The system voltage imposes an indirect constraint on generator capability as it requires generator/auxiliary bus voltages to reach beyond high/low voltage limits (typically +/-5%) in order to deliver the desired maximum amount of power which is otherwise within the GRC. These aspects are discussed in detail and evaluated in [1][2].

A typical station limit constrained GRC is shown at Fig. 1 below.

![Diagram showing GRC and station limits](image)

**Available/Realisable GRC shown as**

**Non-available Lag Capability at Loading Pp:**

\[ X1 = (1 - \frac{Q_{lag}}{Q_{lag_{max}}}) \] (As fraction of Qlag_{GRC})

**Non-available Lead Capability at Loading Pp:**

\[ X2 = (1 - \frac{Q_{lead}}{Q_{lead_{max}}}) \] (As fraction of Qlead_{GRC})

**Fig 1: Capability Curves with Generator/ Auxiliary bus Voltage Constraints Marked**

Even though, these constraints could be alleviated to a large extent by varying tap positions of Generator-step-up-Transformer (called GSU or GT) and auxiliary transformer (AT) but it can be easily seen that the one set of GT & auxiliary transformer tap settings which may give the desired reactive capability for one set of system voltages and loadings, the same taps may not be suitable for another set of system voltages and loadings. Therefore frequent operation of taps would be required in order to achieve desired reactive capability form generator for varying system voltage and loading conditions.

This is the real problem, as many a utilities in India and abroad, either do not provide on-load-tap-changer(OLTC) on generator transformers or even if OLTC is available, they are reluctant to operate the GT taps mainly due to reliability considerations[1, 4].
Hence, it is highly desirable to find out optimum tap positions of GT and auxiliary transformer in order to get maximum lagging and/or leading reactive capability for the expected range of system voltage and loading conditions.

Adibi et al. [2] have computed realisable generator reactive capability at various taps combinations of auxiliary & Generator transformer and selected the best combination of taps which would give adequate reactive capability in both lagging or leading regions. This is a trial and error approach. The motivation in this paper is to propose an algorithm for the same using mathematical programming approaches.

**MATHEMATICAL MODELLING**

The objective of optimisation may be either to achieve the maximisation of both "lagging + leading" area capability or it can alternatively be to achieve the maximum "lagging" area capabilities only, for a range of operating conditions (active loadings and system voltages). The result of optimisation algorithm will give a set of Generator and auxiliary transformer tap settings maximising that objective.

A. **Both "Lagging+Leading" Capability Optimisation:**

The objective function for the optimisation is the normalised non-available area of the GRC curve on both lagging and leading sides. The problem can be mathematically stated as follows:

**Minimise : Objective Function = F**

Where $F = UQLG + UQLD$

**Subject to:**

$T_{\text{min}} \leq T_g \leq T_{\text{max}}$

$T_{\text{amin}} \leq T_a \leq T_{\text{amax}}$

$Q_{\text{gratedmn}} \leq Q_g \leq Q_{\text{gratedmx}}$

Where $T_g$ and $T_a$ are generator transformer and auxiliary transformer taps respectively.

$UQLG$ and $UQLD$ (corresponding to X1 and X2 respectively in Fig.1) are the non-available normalised lagging and leading capability respectively. These are evaluated as follows:

$UQLG = \sum_{i=1}^{S} \sum_{j=1}^{L} \frac{1 - Q_{\text{lag}}(i, j)}{Q_{\text{lag-max}}(i, j)}$

$UQLD = \sum_{i=1}^{S} \sum_{j=1}^{L} \frac{1 - Q_{\text{lead}}(i, j)}{Q_{\text{lead-max}}(i, j)}$

$S$ and $L$ are the nos. of system voltages and loadings over which the objective function is to be optimised.

$Q_{\text{lag-max}}(i, j) = \text{Max lag capability at } L^{\text{th}} \text{ active loading as per GRC}$

$Q_{\text{lead-max}}(i, j) = \text{Max lead capability at } L^{\text{th}} \text{ active loading as per GRC}$

$Q_{\text{lag}}(i, j) = \text{Generator actual available lag capability at a given set of tap at } L^{\text{th}} \text{ loading and } S^{\text{th}} \text{ system voltage}$

$Q_{\text{lead}}(i, j) = \text{Generator actual available lead capability at a given set of tap at } L^{\text{th}} \text{ loading and } S^{\text{th}} \text{ system voltage}$

The above optimisation problem is a non-linear optimisation (NLP). It is transformed into linear programming (LP) problem by using linear sensitivities.

$SUQLG_{TG}, SUQLGT_{TG}, SUQLDT_{TG}$ and $SUQLDT_{TA}$ are the sensitivities of Non-available Lag and Lead capability of generator with respect to change of GT tap ($\Delta T_g$) and Auxiliary Transformer tap ($\Delta T_a$).

With the above sensitivities incorporated the linearised optimisation problem can be stated as follows:

**Minimise, Objective Function = F**

$F = UQG^0 + UQL^0 + SUQLGT_{TG} \cdot \Delta T_g + SUQLDT_{TG} \cdot \Delta T_a + SUQLDT_{TA} \cdot \Delta T_a$

The $UQG^0 + UQL^0$ is the base case cost or objective function. This is a constant term and can be eliminated from a linearised objective function.

Linearization errors are reduced by restricting the total change in controls in one iteration of LP. Successive application of LP generates an optimum solution.

B. **Only "Lag" Capability Optimisation:**

Similar to above, Mathematically the "LAG" capability optimisation problem is stated as follows:

**Minimise:**

Objective Function = $F = UQG$

Where,

$UQG = \sum_{i=1}^{S} \sum_{j=1}^{L} \frac{1 - Q_{\text{lag}}(i, j)}{Q_{\text{lag-max}}(L)}$

$UQG$ is the normalised non-available proportion of normalised 'LAG' capability over a range of system voltage and loading conditions.

Other symbols have usual meaning as in para 3A above.
4. RESULTS:

The proposed optimisation procedure has been used for optimising the reactive capability of a typical 210 MW turbo-generator. A simple 3 bus network is considered (refer Fig. 2) where bus1 is System bus, bus2 is Generator bus, bus 3 is Auxiliary bus. Generator bus is connected to system bus and Auxiliary bus through Generator Transformer and Auxiliary transformer respectively.

The relevant data for the generator & auxiliary system is given below.

PLANT DATA:

Main Parameters for the Study:

**Generator:**
247 MVA, .85 pf, 15.75 +/-5% KV, rated Armature Current 3.054 KA, 50 Hz.

**Auxiliary System:** 6.6 kV +/-5% considered

**Generator Transformer:** 250 MVA, X=0.14 pu

**Auxiliary Transformer:** 2*16 MVA, X=0.06 pu

For the purpose of study, one auxiliary transformer is assumed to be loaded to full 16 MVA at 0.85 pf

Base
MVA=250

![Diagram](image)

Fig. 2: Sample System For Study

Results for the system shown in Fig. 2 are presented below for both “Lag and lead” reactive capability optimisation.

**A. “LAG+LEAD” capability optimisation:**
(for Sys. Volt Range=1.00-1.04 pu, Pg= 50 MW to 210 MW)

Refer Fig. 3a & 3b:

**Plots showing Generator capability with**

- **(i) Initial taps** Tt=0.975 Ta=975 (Fig. 3a)
- **(ii) Optimised taps** Tt=1.016 Ta=976 (Fig. 3b)

The realisable GRC is shown as the hatched area.

It can be seen from the above plots at Fig. 3a and 3b that the realisable reactive capability after optimisation i.e. at optimised taps Tt=1.016 Ta=976 has been considerable improved e.g. the available net capability at Sys Voltage=1.0 pu at maximum and minimum loading (50 & 210 MW) is as follows:

<table>
<thead>
<tr>
<th>Active Power (pu)</th>
<th>Before Optimisation Qgen (pu)</th>
<th>After Optimisation Qgen (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(i.e at Tt=0.975)</td>
<td>(i.e at Tt=1.016)</td>
</tr>
<tr>
<td>Lag</td>
<td>0.2</td>
<td>0.488</td>
</tr>
<tr>
<td>Lead</td>
<td>0.18</td>
<td>-0.41</td>
</tr>
<tr>
<td>Lag</td>
<td>0.23</td>
<td>-0.36</td>
</tr>
<tr>
<td>Lead</td>
<td>0.85</td>
<td>-0.15</td>
</tr>
</tbody>
</table>

Improvement in Qgen:
- Lag: 71% -51%
- Lead: 226% -57%

It can be seen that a larger increase in lagging capability is achieved at the cost of lesser reduction in leading capability. Thus overall increase in available generator capability is achieved.

Results for the same system are presented below for only “Lag” reactive capability optimisation.

**“LAG+LEAD” capability optimisation:**
(for Sys. Volt Range=1.00-1.04 pu, Pg= 50 MW & 210 MW)

Refer Fig. 4a & 4b:

**Plots showing Generator capability with**

- **(i) Initial taps** Tt=0.95 Ta=95 (Fig. 4a)
- **(ii) Optimised taps** Tt=1.0414 Ta=975 (Fig. 4b)

The realisable GRC is shown as the hatched area.

It can be seen from the above plots 4a and 4b that realisable lagging reactive capability after optimisation i.e. at optimised taps Tt=1.0414 Ta=975 has been considerable improved e.g. the available net capability at Sys Voltage 1.0 at maximum and minimum loading (50 & 210 MW) is as follows:

<table>
<thead>
<tr>
<th>Active Power (pu)</th>
<th>Before Optimisation Qgen (pu)</th>
<th>After Optimisation Qgen (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(i.e at Tt=0.95)</td>
<td>(i.e at Tt=1.0414)</td>
</tr>
<tr>
<td>Lag</td>
<td>0.2</td>
<td>0.663</td>
</tr>
<tr>
<td>Lead</td>
<td>-0.24</td>
<td>-0.034</td>
</tr>
<tr>
<td>Lag</td>
<td>0.85</td>
<td>0.5</td>
</tr>
<tr>
<td>Lead</td>
<td>-0.19</td>
<td>-0.155</td>
</tr>
</tbody>
</table>

It can be seen that before optimisation NO lagging capability was available. However at optimised tap a
vast amount of lagging capability (almost the entire lagging GRC area) is achieved. Thus the objective of LAG capability increase is achieved.

5. CONCLUSIONS:
In this paper an algorithm to optimise the generator realisable reactive capability has been presented. The difference between the manufacturer's furnished GRC and the actual available reactive capability is due to station constraints. This difference also depends on the generator loading conditions and system voltage. The optimisation algorithm presented here recommends the most suitable the generator transformer and auxiliary transformer taps positions so as to minimise the above difference over the range of loading and system voltages of interest. Results for a typical 210 MW generator clearly demonstrate the significant benefits which can be obtained using optimised taps.

REFERENCES: