Performance Enhancement of Static Var Compensator (SVC) by Modifying Its Steady State Operating Point.

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Abstract:  
This paper presents the modeling of a power system of two-plants connected by a long transmission line. This system is simulated by Matlab/ Simulink program to illustrate performance enhancement of SVC during large disturbance such as three phase short circuit fault incidence on this power system which is compensated by SVC at the middle point of the transmission line. The SVC performance is studied in both of its operation modes, voltage regulator operation mode and susceptance regulator (modified operating point) operation mode. The simulation results showed that during a severe contingency the SVC in susceptance regulation mode has succeeded in stabilizing the network compared to the voltage regulation mode.

Keyword: FACTS, Static Var Compensator SVC, Susceptance regulator, variable reference voltage, Thyristor Controlled Reactor TCR, Thyristor Switched Capacitor TSC.
تحسين أداء معوض القدرة الغير فعاله الستاتيكي
بتغيير نقطة عمله.

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1. Introduction
The electrical power network grows with enormous complexity. In such a complex network with the conventional control mechanisms, there is a lack of controllability of the active and reactive power flows in energized networks. In a complex interconnected ac transmission system, the power flow finds many paths on its way from the source to load. In such networks a load flow study must be performed to find the active and reactive power flows on all the times. Its impedance and voltages at the terminals determine the flow of active and reactive powers on the line. Even though we obtain the reliability of power supply, no control exists on line loading. By adding shunt and series elements, the line impedances may be altered. Since the parameters of the transmission lines of the complex network cannot be altered, the series and shunt connected FACTS devices help in altering the line parameters and the efficiency of the network is increased. Power system stability may be defined as that property of a power system that enable it to remain in a state of equilibrium under normal operating conditions and to regain an acceptance state of equilibrium after being subjected to disturbance [1].
Flexible AC Transmission Systems (FACTS) devices with a suitable control strategy have the potential to increase the system stability margin [2, 3]. Shunt FACTS devices play an important role in
reactive power flow in the power network. In large power systems, low frequency electro-mechanical oscillations often follow the electrical disturbances. Generally, power system stabilizers (PSS) are used in conjunction with Automatic Voltage Regulators (AVR) to damp out the oscillations [3]. However, during some operating conditions this device may not produce adequate damping and other effective alterations are needed in addition to PSS [4, 5]. Another means to achieve damping is to use the same shunt FACTS device Static Var Compensator (SVC) designed with auxiliary controllers [6]. Therefore SVC is more effective and if accommodated with supplementary controller, by adjusting the equivalent shunt capacitance, SVC will damp out the oscillations and improves the overall system stability [7]. The system operating conditions change considerably during disturbances. Various approaches are available for designing auxiliary controllers in SVC. In [8]a proportional integral derivative (PID) was used in SVC. It was found that significant improvements in system damping can be achieved by the PID based SVC. Although PID controllers are simple and easy to design, their performances deteriorate when the system operating conditions vary widely and large disturbances occur. This paper presents the modeling of a power system of two-plants connected by a long transmission line, this system is simulated by Matlab/Simulink program to illustrate performance enhancement of the SVC and its impact on transient stability of the power system when it is designed as a susceptance regulator or by modifying its operating point. The SVC performance is studied in both of its operation mode, voltage regulator and susceptance regulator operation modes. The simulation results showed that during a severe contingency the SVC in susceptance regulation mode managed to keep the power system stable compared to the voltage regulation operation mode of the SVC.

2. Static Var Compensator

(a) Configuration of SVC

SVC provides an excellent source of rapidly controllable reactive shunt compensation for dynamic voltage control through its utilization of high-speed thyristor switching/controlled devices [9]. A SVC is typically made up of coupling transformer, thyristor valves, reactors, capacitance (often tuned for harmonic filtering).
(b) Advantages of SVC
The main advantage of SVCs over simple mechanically switched compensation schemes is their near-instantaneous response to change in the system voltage. For this reason they are often operated at close to their zero-point in order to maximize the reactive power correction [10]-[13]. They are in general cheaper, higher-capacity, faster, and more reliable than dynamic compensation schemes such as synchronous compensators (condensers).

(c) Control Concept of SVC
An SVC is a controlled shunt susceptance (B) as defined by control settings that injects reactive power (Q) into the system based on the square of its terminal voltage. Figure 1 illustrates a TCR SVC, including the operational concept. The control objective of the SVC is to maintain a desired voltage at the high-voltage bus. In the steady-state, the SVC will provide some steady-state control of the voltage to maintain the high-voltage bus at a pre-defined level.

Figure 1: SVC with control concept [14]
If the high-voltage bus begins to fall below its set point range, the SVC will inject reactive power \( (Q_{\text{net}}) \) thereby increasing the bus voltage back to its net desired voltage level. If bus voltage increases, the SVC will inject less (or TCR will absorb more) reactive power, and the result will be to achieve the desired bus voltage. From Figure 1, \( +Q_{\text{cap}} \) is a fixed capacitance value (FC) or may be Thyristor Switched Capacitor TSC, therefore the magnitude of reactive power injected into the system, \( Q_{\text{net}} \), is controlled by the magnitude of \( -Q_{\text{ind}} \) reactive power absorbed by the TCR. The fundamental operation of the thyristor valve that controls the TCR is described here. The thyristor is self commutated at every current zero, therefore the current through the reactor is achieved by gating or firing the thyristor at a desired conduction or firing angle with respect to the voltage waveform [15].

3. V-I Characteristic of SVC
The steady-state and dynamic characteristics of SVCs describe the variation of SVC bus voltage with SVC current or reactive power. Two alternative representations of these characteristics are shown in Figure 2: part (a) illustrates the terminal voltage–SVC current characteristic and part (b) depicts the terminal voltage–SVC reactive-power relationship.

3.1 Dynamic Characteristic
Reference Voltage, \( V_{\text{ref}} \): This is the voltage at terminals of the SVC during the floating condition, that is, when the SVC is neither absorbing nor generating any reactive power. The Reference voltage can be varied between the maximum and minimum limits \( V_{\text{ref max}} \) and \( V_{\text{ref min}} \) by the SVC control system. Typical values of \( V_{\text{ref max}} \) and \( V_{\text{ref min}} \) are 1.05 pu and 0.95 pu, respectively.

Linear Range of SVC Control: This is the control range over which SVC terminal voltage varies linearly with SVC current or reactive power, as the latter is varied over its entire capacitive-to-inductive range.

Slope or Current Droop: The slope or droop of the V-I characteristic is defined as the ratio of voltage-magnitude change to current-
magnitude change over the linear-controlled range of the compensator. Thus slope $K_{SL}$ is given by

$$K_{SL} = \frac{\Delta V}{\Delta I} \Omega$$

.........................(1)

where $\Delta V$ = the change in voltage magnitude (V)
$\Delta I$ = the change in current magnitude (A)

The per unit value of the slope is obtained as

$$K_{SL,pu} = \frac{\Delta V/V_r}{\Delta I/I_r}$$

.........................(2)

Where $V_r$ and $I_r$ represent the rated values of SVC voltage and current, respectively.

For $\Delta I = I_r$

$$K_{SL} = \frac{\Delta V(at \ I_r \ or \ Q_r)}{V_r} \ pu$$

$$= \frac{\Delta V(at \ I_r \ or \ Q_r)}{V_r} .100\%$$

...............................(3)

where $Q_r$ represents the rated reactive power of SVC.

Thus the slope can be defined alternatively as the voltage change in percent of the rated voltage measured at the larger of the two—maximum inductive- or maximum capacitive-reactive-power outputs, as the larger output usually corresponds to the base reactive power of the SVC. In some literature, the reactive power rating of the SVC is defined as the sum of its inductive and capacitive rating. The slope is often expressed as an equivalent reactance:

$$X_{SL} = K_{SL} \text{ in pu}$$

.........................(4)

The slope can be changed by the control system of the SVC. The slope is usually kept within 1–10%, with a typical value of 3–5%. Although the SVC is expected to regulate bus voltage, that is, maintain a flat voltage-current profile with a zero slope, it becomes desirable to incorporate a finite slope in the V-I characteristics.

Overload Range: When the SVC traverses outside the linear-controllable range on the inductive side, the SVC enters the overload zone, where it behaves like a fixed inductor.
Overcurrent Limit: To prevent the thyristor valves from being subjected to excessive thermal stresses, the maximum inductive current in the overload range is constrained to a constant value by an additional control action.

The steady-state V-I characteristic of the SVC is very similar to the dynamic V-I characteristic except for a deadband in voltage, as depicted in Figs. 2 (a) and (b). In the absence of this deadband, in the steady state the SVC will tend to drift toward its reactive-power limits to provide voltage regulation. It is not desirable to leave the SVC with very little reactive-power margin for future voltage control or stabilization excursions in the event of a system disturbance. To prevent this drift, a deadband about $V_{\text{ref}}$ holds the $I_{\text{SVC}}$ at or near zero value, depending on the location of the deadband. Thus the reactive power is kept constant at a setpoint, typically equal to the
MVA output of the filters. This output is quite small; hence the total operating losses are minimized [17], [18]. A slow susceptance regulator is employed to implement the voltage deadband, i.e. to modify the SVC operating point or reference voltage (V_{ref}).

4. Power System Modeling
The modeled power system is shown in figure 3 which is composed of a 1000 MW generation plant (G1) connected through a step up transformer (Transformer 1) 13.8 kv/500kv and of capacity 1000MVA to a long 500kv, 700 km transmission line. The load center is modeled by a 5000 MW resistive and 100 Mvar inductive load. The load is fed by a local generation plant (G2) of 8500 MW through a step up transformer (Transformer 2) 13.8 kv/500 kv and of capacity 10000 MVA. A Static Var Compensator (SVC) of ± 200 Mvar is connected to bus bar B2. The system is simulated by matlab/simulink environment as shown in appendix A. In order to start the simulation in steady-state the model must be first initialized for the synchronous machines and regulators to the desired load flow. The machine (G1) is considered as PV generator, i.e. the load flow will be performed with the machine controlling its active power and its terminal voltage. Machine (G2) will be used as a swing bus for balancing the power. The load flow simulation result is given in appendix B.

![Figure 3 The Model of the simulated power system](image-url)
5. Modeling of SVC in a Voltage Regulator Mode

The block diagram of a general TSC–TCR type of SVC control system is depicted in Figure 4. This control system incorporates features of simple voltage control i.e this block is for the SVC which is operating in voltage regulation mode (the voltage is regulated within limits).

![Diagram of SVC in voltage regulator mode](image)

**Figure 4 Model of SVC in voltage regulator mode [16]**

This basic block of SVC controller consists of:

- **Measuring circuit:** This circuit provides the necessary inputs to the SVC controller for performing its control operations. The two main measured inputs to the SVC controller are voltage and current whereas other needed signals may be derived within the control system.

- **Voltage regulator:** The SVC voltage regulator processes the measured system variables and generates output signal that is proportional to the desired reactive-power compensation. Different control variables and transfer functions of the voltage regulator are used, depending on the specific SVC application. The measured control variables are compared with a reference signal, usually $V_{ref}$, and an error signal $V_e$ is input to the controller transfer function. The output of the controller is a per-unit susceptance signal $B_{ref}$ (shown in figure 7), which is generated to reduce the error signal to...
zero in the steady state. The susceptance signal is subsequently transmitted to the next stage of the controller which is thyristor susceptance control.

$K_{SL}$: A small slope or droop (3–5%) is typically incorporated into the steady-state characteristics of SVCs to achieve specific advantages. The SVC current is explicitly measured and multiplied by a factor $K_{SL}$ representing current droop before feeding as a signal to the summing junction. The sign of this signal is such that it corresponds to an increase of reference voltage for inductive SVC currents and a decrease of the reference voltage for capacitive SVC currents. Simple integral control finds most common usage in voltage regulator.

6. Thyristor susceptance control
   It consists of
   (i) Gate Pulse Generation
   The susceptance reference output from the voltage regulator is transmitted to the gate pulse–generation (GPG) unit, which produces appropriate firing pulses for all the thyristor-controlled and thyristor-switched devices of the SVC so that the desired susceptance is effectively made available at the SVC bus to achieve the specified control objectives.
   The simulation design of this stage is done by:
   1. Calculating the number of TSC branches to be switched in to meet the capacitive susceptance demand and also to allow an excess capacitive susceptance to appear in the SVC which is achieved by dividing the SVC susceptance reference output from the voltage regulator, $B_{ref}$, by the susceptance of one capacitor bank, $B_C$. The quotient rounded off to the next integer corresponds to the number of capacitor banks required, say, $n_C$. The difference between the total capacitive susceptance $n_C B_C$ and $B_{ref}$ provides the inductive susceptance to be realized by TCR through firing control.
   2. Calculating the magnitude of TCR-inductive susceptance to offset the surplus capacitive susceptance.
   3. Determining the sequence in which the TSC connections should be actuated, depending on the existing polarity of charges on the different capacitors, and thereby ensures transient-free capacitor switching.
4. Computing the firing angle for TCR thyristors for implementing the desired TCR-inductive susceptance at the SVC terminals.

(ii) The Linearizing Function
As an approximate design of SVC model the desired susceptance output, $B_{ref}$, of the voltage regulator is to be entirely implemented through the TCR, that is, there are no fixed or switchable capacitors. Then the implementation of the voltage-regulator output $B_{ref}$ as an actual installed susceptance $B_{SVC}$ takes place through an intermediate stage of the firing-angle calculation, as shown in Figure 5. Because the relationship between the firing angle $\alpha$ and the susceptance $B_{SVC}$ expressed as $F_1(\alpha)$ is nonlinear, it necessitates the inclusion of a linearizing function $F_2(\alpha)$ to ensure that

$$F_2(\alpha)F_1(\alpha) = 1 \quad (5)$$

where

$$F_2(\alpha) = [F_1(\alpha)] \quad (6)$$

For the case of a single TCR alone, $F_1(\alpha)$ is expressed as

$$F_1(\alpha) = B_{SVC} = \frac{2\pi - 2\alpha + \sin 2\alpha}{\pi} \quad (7)$$

Thus

$$F_2(\alpha) = \frac{\pi}{2\pi - 2\alpha + \sin 2\alpha} \quad (8)$$

The function $F_2(\alpha)$ represents the calculation of the firing angle, corresponding to $B_{ref}$ if all of the $B_{ref}$ is to be implemented on the TCR.

\[ \text{Figure 5 The linearization function.} \]

(iii) The Synchronizing System
The purpose of the synchronizing system is to generate reference pulses in synchronism with the fundamental component of system voltage. These pulses are then used by the gate pulse generation unit
to time the firing pulses to the TCR and TSCs. The synchronizing system that is employed in this model is based on phase locked loop (PLL), the block diagram of PLL model is shown in figure 6, this PLL not only provides a signal at the zero-crossing instant of the fundamental voltage, but it also generates the necessary timing-clock signals that are phase-locked to the fundamental frequency for the digital counters that count the firing angle.

![Figure 6 PLL model of Synchronizing System](image)

6. Modeling of SVC in a Susceptance Regulator Mode
The block diagram of the susceptance regulator SVC is shown in figure 7. The susceptance regulator shown compares the voltage-regulator output susceptance $B_{\text{ref}}$ with a setpoint $B_{\text{set}}$. The $B_{\text{set}}$ is usually chosen to be the fundamental-frequency reactive-power contribution of the permanently connected harmonic filters of the SVC. In these cases, the $B_{\text{set}}$ corresponds to a near-floating-state operation of the SVC. The error signal is transmitted through an integral control, and a corrective voltage contribution is applied to the voltage-reference junction.
6.1 Operation of Susceptance (Reactive-Power) Regulator Mode

The SVC requires a substantial reactive-power reserve capacity to improve system stability. In the event of a disturbance, the fast-voltage regulator control uses a significant part of the reactive-power range of the SVC to maintain a pre-specified terminal voltage. If the SVC continues to be in this state, not enough reactive-power capacity may be available for it to respond effectively to a subsequent disturbance. A slow susceptance (or var) regulator is provided in the control system that changes the voltage reference to return the SVC to a preset value of reactive-power output, which is usually quite small. Other neighboring compensating devices, such as mechanically switched capacitors or inductors, can then be employed to take up the required steady-state reactive-power loading. The operation of the susceptance regulator is illustrated in figure 8. Let the SVC initially be at the steady-state operating point 1, which marks the intersection of the system load line and SVC V-I characteristics. If a sudden disturbance occurs in the system, reducing the SVC bus voltage by $\Delta V_T$, the SVC moves rapidly to operating point 2 by the action of the voltage regulator. This operating point is described by the intersection of the new system load line and the SVC V-I characteristic. If this decrease in voltage
persists for some time, the susceptance regulator, through its slow integrator action, will modify the SVC reference voltage by $\Delta V_{SR}$ (shown in figure 7) and bring the SVC steady-state operating point to 3. Now, although the SVC voltage has been reduced below the desired reference, the SVC reactive power range is still available for coping with any system contingency. The neighboring var sources (Mechanically switched capacitors MSC, Mechanically switched reactors MSR, and LTC transformers are some of the major neighboring reactive-power devices that constitute the overall static var system and thus need to be controlled appropriately) may then be switched as shown in figure 7 by the block titled (Mechanical Equipment Control Logic) to raise the SVC voltage to the desired value. The SVC matlab/Simulink model is shown in appendix C.

![Diagram of SVC susceptance regulator](image)

Figure 8 Operation of the SVC susceptance regulator[16]

7. Simulation Results and Discussion
7.1 The Power System without Disturbance.
Figure 9 shows the simulation results for the system which is operating without disturbance and without SVC. Figure 9a shows the variation of the rotor angle difference in degrees (d-theta) of the two machines (G1 and G2). Figure 9b shows the angular speed of the two generators (G1 and G2) it is clear that the two machines are...
synchronized and rotating at the same speed. Figure 9c shows the terminal voltages of G1 and G2 (Vt1 and Vt2 respectively). Figure 9d shows the transmitted power through the transmission line.

(a)

(b)
Figure 9: (a) Rotor Angle Difference (deg.), (b) Angular speed of G1 and G2 (pu), (c) Terminal Voltage of G1 and G2 (pu), (d) line Power (MW).

7.2 The Power System with 3-Phase to Ground Fault without SVC.
A 3-phase to ground fault is applied at bus bar (B1) at \( t = 10 \) sec and the fault duration is 13.2 cycles of the power frequency (or fault duration time is 0.22 seconds), the power system is simulated without SVC, the impact of this severe contingency is to make the system unstable and the generators is going out of step. Figure 10 shows the simulation results of this severe disturbance.
Figure 10: (a) Rotor Angle Difference (deg.), (b) Angular speed of G1 and G2 (pu), (c) Terminal Voltage of G1 and G2 (pu), (d) line Power (MW).
7.3 The Power System with 3-Phase to Ground Fault with SVC in Voltage Regulating Mode. 

The power system is simulated as in 7.2 above but with SVC operating in voltage regulator mode, the simulation results showed that in this mode of operation the SVC does not managing in keeping this power system to be stable and the two plants going out of step as in the simulation results of 7.2 above. Figure 11 shows that the voltage regulator control uses a significant part of the reactive power range of the SVC to maintain a pre-specified terminal voltage. If the SVC continues to be in this state, not enough reactive-power capacity may be available for it to respond effectively to the disturbance.

Figure 11 Reactive-Power Range of SVC

7.4 The Power System with 3-Phase to Ground Fault with SVC in Susceptance Regulating Mode. 

A 3-phase to ground fault is applied at bus bar (B1) at t = 10 sec and the fault duration is 13.2 cycles of the power frequency (or fault duration time is 0.22 seconds), the power system is simulated with SVC, the impact of the SVC is to make the system stable and the generators is keeping in step. Figure 12 shows the simulation results of this case.
Rotor Angle Difference (deg)

Angular Speed of G1 and G2 (pu)

Terminal Voltage of G1 and G2 (pu)
7.5 The Power System with 3-Phase to Ground Fault Duration of (0.25 sec.) with SVC in Susceptance Regulating Mode.

A 3-phase to ground fault is applied at bus bar (B1) at $t = 10$ sec and the fault duration is 15 cycles of the power frequency (or fault duration time is 0.25 seconds), the power system is simulated with
SVC, the impact of the SVC is to make the system stable and the generators is keeping in step. Figure 13 shows the simulation results of this case.
Terminal Voltage of G1 and G2 (pu)

Line power (MW)

(c)

(d)
Figure 13: (a) Rotor Angle Difference (deg.), (b) Angular speed of G1 and G2 (pu), (c) Terminal Voltage of G1 and G2 (pu), (d) line Power (MW), (e) Reactive-Power Capacity of SVC.

8. Conclusion
1- It is concluded that SVC (Static VAR Compensator) will successfully control the dynamic performance of power system and voltage regulation of the power system. Using the SVC in susceptance regulator is more efficient in stabilizing the power system during severe contingencies. The range of reactive power control can be increased by using the susceptance (reactive-power) regulator.

2- Figure 10 shows the reactive power capacity of SVC when simulated in a voltage regulator mode where at the instant of fault incidence (t = 10 sec.) the reactive power was about 1.5 pu whereas figures 11e and 12e show the reactive power capacity of SVC when simulated in susceptance regulator mode and at the same instant of fault incidence is about 2.75 pu, this difference in reactive power capacity of the SVC for the two modes of operation causes the difference in SVC performance during the fault, where the first mode of operation could not make the system to stabilized after fault clearing whereas the second mode of operation could.
Appendix A
Matlab/ Simulink simulation of the power system model

[Diagram of the power system model with labels and connections]
Appendix B

Load flow simulation results

Machine: G1 1000 MVA, 13.8 KV r.m.s
Bus Type: PV generator

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>$V_{an}$ phase</td>
<td>51.41°</td>
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<tr>
<td>$V_{ab}$</td>
<td>13800 Vrms [1 pu] 81.41°</td>
</tr>
<tr>
<td>$V_{bc}$</td>
<td>13800 Vrms [1 pu] -38.59°</td>
</tr>
<tr>
<td>$V_{ca}$</td>
<td>13800 Vrms [1 pu] -158.59°</td>
</tr>
<tr>
<td>$I_a$</td>
<td>39750 Arms [0.9501 pu] 50.51°</td>
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<tr>
<td>$I_b$</td>
<td>39750 Arms [0.9501 pu] -69.49°</td>
</tr>
<tr>
<td>$I_c$</td>
<td>39750 Arms [0.9501 pu] 170.51°</td>
</tr>
<tr>
<td>$P$</td>
<td>9500 MW [0.95 pu]</td>
</tr>
<tr>
<td>$Q$</td>
<td>15024 MVar [0.01502 pu]</td>
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<tr>
<td>$P_{mech}$</td>
<td>952.58 MW [0.9526 pu]</td>
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<tr>
<td>Torque</td>
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<tr>
<td>$V_f$</td>
<td>1.4386 PU</td>
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Machine: G2 8500 MVA, 13.8 KV r.m.s
Bus Type: Swing generator

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<td>$V_{bc}$</td>
<td>13800 Vrms [1 pu] -90.00°</td>
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<td>13800 Vrms [1 pu] -150.00°</td>
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<td>$I_a$</td>
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<td>$I_b$</td>
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<td>$I_c$</td>
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<td>$P$</td>
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<td>$Q$</td>
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<td>Torque</td>
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<td>$V_f$</td>
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References


