Effective Use of A Novel Designed Inverter for Distribution System to Improve Power System Stability and Voltage Profiles

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Contents

Background

Grid problems due to Increase in renewable energy (RE) generations
- Decrease in system Inertia
- Degradation of system stability and security in transmission system (Frequency Stability, Transient Stability, Steady Stage Stability)
- Voltage problem in distribution system (DS) as well as in transmission system

New Types of Inverters
- Grid following inverter, Grid forming inverter, etc.

Contents

Potential of new Inverter, Effective method to solve grid problems
- Development of New Type of Single Phase Synchronous Inverter (SSI)
- Effectiveness of SSI for Enhancement of System Stability
- A New Method for DS voltage control using DGs including SSIs.
Features of Proposed SSI

“Core and Shell” Non-Interference Design Concept
- Core: Important Dynamics designed for Grid Stability
  SM model with AVR, Governor, (PSS, LFC, w/wo FRT)
- Shell: The other parts for inverter control
- SSI dynamics are purely governed by “Core” design.

Other Features
- VSM having synchronous torque, realizing flexible single-phase connection to grid, to microgrid, to other SSIs.
- Flexible Connection and Disconnection
- Overcurrent suppression during grid side faults
"Core and Shell" Non-interference Concept

- Core and shell can be designed independently
- Core dynamics designed for grid stability can be accurately realized.

Realization of Design Concept

Designed dynamics (1) is realized in (2)
(1) Simulation using Core Dynamics only
(2) Simulation of Whole SSI Dynamics
Outline of Proposed SSI (1kVA, 100V)

- Battery
  - Charge/Discharge
  - \( V_{\text{dc}} \) is controlled
  - \( V_{\text{dc}} \) is controlled
- \( V_{\text{dc}} \) is controlled
- DC voltage control
- DC side voltage
- DC/DC converter
- Digital controller
- Internal frequency
- Flexible connection
- Switch: ON (t=0 s)
- Flexible sychronization
- Overcurrent suppression
- Fault
- SSIs
- DC/DC converter
- Fault
Effectiveness of SSI to Enhance System Stability

Case 1: Original operating condition.
Case 2: 60% of the generation is replaced by PV.
Case 3: Half of PV inverters are replaced by SSI.

<table>
<thead>
<tr>
<th>Cases</th>
<th>G Output [p.u.]</th>
<th>Total PV Output [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(G1+G2+G3)</td>
<td>Regular INV (Negative load)</td>
</tr>
<tr>
<td>Case 1</td>
<td>3.196 (100%)</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>1.278 (40%)</td>
<td>1.918 (60%)</td>
</tr>
<tr>
<td>Case 3</td>
<td>1.278 (40%)</td>
<td>0.956 (30%)</td>
</tr>
</tbody>
</table>

SSI Core Dynamics

\[
\dot{\omega} = \frac{1}{M} \left\{ P_m - P_e - D(\omega - \omega_0) \right\} \quad \text{Sync Machine}
\]
\[
\dot{\theta} = \omega - \omega_0 \quad \text{Gov}
\]
\[
\dot{P}_m = \frac{1}{T_{GOV}} \left\{ - (P_m - P_{m0}) - K_{GOV} (\omega - \omega_0) \right\} \quad \text{Gov}
\]
\[
\dot{E} = \frac{1}{T_{AVR}} \left\{ - (|E| - |E_0|) - K_{AVR} (|V_G| - |V_{G0}|) \right\} \quad \text{AVR}
\]
Generator Swing: $\theta$ of G2 for small disturbance (CT=0.01)

- **Case 1**
  - Light loading

- **Case 2**
  - (PV)

- **Effect of SSI**
  - Case 3
  - (PV+SSI)
Generator Swing: $\omega$ of G2 for small disturbance ($CT=0.01$)

- **Case 1**
- **Case 2** (PV)
- Effect of SSI
- **Case 3** (PV+SSI)
Generator Swing: $\theta$ of G2 for large disturbance ($CT=0.46$)

Case 1
Case 2 (PV)
Effect of SSI
Case 3 (PV+SSI)
Voltage Problem in Distribution System (DS)

- Serious voltage fluctuation due to PV installation.
- Large investment is required in DS to solve it.

Problem concerned with local prosumers

- PV power cannot be transferred due to voltage limit.
- The voltage condition is different depending on the location of connecting point, which may cause fairness problem.

Effective Solution using DGs including SSI
Proposed Voltage Control based on BM Scheme

Blackboard Memory
- Common Memory among Independent Agents

Management Agent
- OPF computation using real-time BM data to maximize total PV profits, and to send Nodal prices of P and Q to BM.

Local Agents (Prosumers)
- Sending local info to BM
- Maximizing own profit by selling P and Q for the prices on BM

Distribution System (DS)
66kV/6.6kV  6.6kV/200/100V

SS

Prosumers
**Global OPF Formulation**

**Objective:** Maximizing total profit of PV generation in DS

\[
\max_{P_i, \, i \in N} \sum_{i \in N} w_p P_i
\]

\(w_p: \text{price of PV power}\)

**DS Constraints:**

1. **Power Flow Eqn**
   \[\begin{bmatrix} P_i - P_{li} \\ Q_i - Q_{li} \end{bmatrix} = \begin{bmatrix} h_{pi}(V, \delta) \\ h_{qi}(V, \delta) \end{bmatrix}\]

2. **Voltage Limit**
   \(V_i \leq V_{\max,i}\)

**Inverter Constraints:**

3. **SSI Capacity**
   \(P_i^2 + Q_i^2 \leq S_i^2\)

4. **PV Generation**
   \(0 \leq P_i \leq \bar{P}_i\)

5. **PF Constraint**
   \(\gamma_i P_i \leq Q_i \leq \gamma_i P_i\)

\(\gamma_i = \tan \varphi_{\min,i}\)
Procedure for Optimal DS Operation

Management Agent (Global OPF)
(Maximizing Total Profit of PV Powers)
\[
\max_{p_i, i \in N} \sum_{i \in N} w_p p_i
\]
Subject to DS Constrains
Inverter Constraints

Local Agent \(i\) (Local Problem)
(Maximizing Own Profit \(f_i\))
\[
\max_{p_i, q_i} f_i = w_p p_i + p_{Pi} p_i + p_{Qi} q_i
\]
Subject to
Inverter Constraint

\(p_{Pi}\) and \(p_{Qi}\): Shadow Prices of \(P_i\) and \(Q_i\) for Voltage Control of Node \(i\)
(Nodal Price)

This method guarantees that: Global OPF solution = Local solutions
Simulation of Proposed Voltage Control

System Model

Case Setting

[Case 1]
Conventional operation under FIT scheme
> Maximum P output with Q=0 while V<Vmax
> When hitting Vmax, decreasing P with Q, pf=0.85 to keep Vmax.
> P=Q=0 when V>Vmax.

[Case 2]
Proposed Method
Dynamic Nodal Pricing for P and Q

Common setting

Price of P: \( w_{P_i} = 22.68 \text{ [V/kWh]} \)

Voltage Limit: \( V_{max,i} = 1.02 \text{ [p.u.]} \)

Power factor limit of Inverter outputs:
\( \cos\phi_{min,i} = 0.85 \)  \( (\gamma_i = 0.6197) \)

6.6 kV Single Phase Feeder
Load: 60kW/node
PV Capacity: 150kW/node
DS Operation when 120kW solar radiation

- Total PV generation (P) is increased in Case 2 due to the total profit maximization.
- Profits of local agents are equalized due to nodal pricing for P and Q.

<table>
<thead>
<tr>
<th></th>
<th>Conventional Method (Case1)</th>
<th>Proposed Method (Case2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS1</td>
<td>22.68</td>
<td>0</td>
</tr>
<tr>
<td>PCS2</td>
<td>1.017</td>
<td>120</td>
</tr>
<tr>
<td>PCS3</td>
<td>1.020</td>
<td>116.8</td>
</tr>
<tr>
<td>PCS4</td>
<td>1.020</td>
<td>65.4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
24 hour Simulation

PV output & Load patterns

Voltages without control

Max Voltage
Results of 24 hour simulation

- Active power P (kW)

[case 1] Conventional Method

- Voltage (pu)

[case 2] Proposed Method
Results of 24 hour simulation

- Reactive power Q (kVAr)
- Power factor

[case 1] Conventional Method

[case 2] Proposed Method
Summary of 24 hour simulation

- Total PV generation (P) is increased in Case 2 due to the total profit maximization.
- Profits of local agents are equalized due to nodal pricing for P and Q.

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<th>Conventional Method (Case1)</th>
<th>Proposed Method (Case2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$ [kWh]</td>
<td>$Q$ [kVARh]</td>
</tr>
<tr>
<td>PCS1</td>
<td>866.4</td>
<td>0</td>
</tr>
<tr>
<td>PCS2</td>
<td>866.4</td>
<td>0</td>
</tr>
<tr>
<td>PCS3</td>
<td>831.9</td>
<td>177.8</td>
</tr>
<tr>
<td>PCS4</td>
<td>455.6</td>
<td>178.3</td>
</tr>
<tr>
<td>Total</td>
<td>3020.3</td>
<td>356.1</td>
</tr>
</tbody>
</table>
Conclusions

- A new type of single phase synchronous inverter (SSI) is being developed based on “Core and Shell” non-Interference design concept for flexible and effective implementation of grid stabilizing dynamics.

- Simulation study has shown that SSI has potential for considerably improving grid stability.

- A new method for voltage control of distribution system is investigated for fully utilizing the inverters, which can increase the PV generations, equalize prosumers profits, and reduce additional investment in DS.
References


Thank you!

The 15th International Workshops on Electric Power Control Centers (EPCC 15)
May 12 – 15, 2019, Reykjavik, Iceland
“Effective Use of A Novel Designed Inverter for Distribution System to Improve Power System Stability and Voltage Profiles”
By Naoto Yorino, Yutaka Sasaki, Shinya Sekizaki (Hiroshima University)
Improvement of the system damping by using SI.

Contingency 3LG-Fault
Core Dynamics

Xd’ generator model with AVR and Gov

Power Swing Equation:

\[ M^{inv} \frac{d^2 \theta^{inv}_m}{dt^2} + D^{inv} \frac{d \theta^{inv}_m}{dt} + K^{inv} \theta^{inv}_m = P^{inv}_m + P^{inv}_{gov} - P^{grid}_e \]

\[ P^{inv}_{gov} = \frac{K^{inv}_{gov}}{1 + T^{inv}_{gov}s} \left( \omega_{ref} - \omega^{inv} \right) \]

Stability Evaluation by using Eigenvalue
**Eigenvalue Analysis**

- ○: Conventional Gen. only
- ○: Conventional Gen. + SI (the capacity of 10% G₁)
- ○: Conventional Gen. + SI (the capacity of 20% G₁)

The effect of stabilization by using SSI.