Table 1. Load data for the Danish 14-bus network [14].

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Q(MW) | P(MW) | Load | Q(MW) | P(MW) | Load |
| 0.0050 | 0.01725 | L1-DR | 0.02847 | 0.0977 | L1 |
| 0.0050 | 0.01725 | L2-DR | 0.02847 | 0.0977 | L2 |
| 0.0050 | 0.01725 | L3-DR | 0.02847 | 0.0977 | L3 |
| 0.0317 | 0.1086 | L4-DR | 0.1796 | 0.6156 | L4 |
| 0.0201 | 0.0689 | L5-DR | 0.1139 | 0.3908 | L5 |
| 0.0864 | 0.3163 | L6-DR | 0.4896 | 1.7926 | L6 |
| 0.0208 | 0.1758 | L7-DR | 0.1181 | 0.9962 | L7 |
| 0.1263 | 0.4098 | L8-DR | 0.7157 | 2.3222 | L8 |
| 0.0334 | 0.2973 | L9-DR | 0.1895 | 1.6847 | L9  |
| 0.0576 | 0.2484 | L10-DR | 0.3264 | 1.4076 | L10 |
| 0.0246 | 0.135 | L11-DR | 0.1394 | 0.765 | L11 |

Table 2. ROCOFL\*pv amounts.

|  |  |
| --- | --- |
| Load | ROCOFL\*pv (Hz/s) |
| First scheme | Second scheme | Third scheme | Fourth scheme | Fifth scheme |
| L1 | -0.3825 | -0.3782 | -0.425 | -0.4165 | -0.408 |
| L1-DR | -0.0675 | -0.0667 | -0.075 | -0.0735 | -0.072 |
| L2 | -0.3825 | -0.3782 | -0.425 | -0.4165 | -0.408 |
| L2-DR | -0.0675 | -0.0667 | -0.075 | -0.0735 | -0.072 |
| L3 | -0.3825 | -0.3782 | -0.425 | -0.4165 | -0.408 |
| L3-DR | -0.0675 | -0.0667 | -0.075 | -0.0735 | -0.072 |
| L4 | -2.5075 | -2.4225 | -2.754 | -2.72 | -2.652 |
| L4-DR | -0.4425 | -0.4275 | -0.486 | -0.48 | -0.468 |
| L5 | -1.5725 | -1.53 | -1.5725 | -1.717 | -1.67 |
| L5-DR | -0.2775 | -0.27 | -0.2775 | -0.303 | -0.2955 |
| L6 | -7.35 | -7.225 | -7.361 | -7.9815 | -7.8 |
| L6-DR | -1.2975 | -1.275 | -1.299 | -1.4085 | -1.377 |
| L7 | -4.0375 | -3.9525 | -4.4455 | -4.386 | -4.2925 |
| L7-DR | -0.7125 | -0.6975 | -0.7845 | 0.774 | -0.7575 |
| L8 | -9.6475 | -9.435 | -9.605 | -10.446 | -10.208 |
| L8-DR | -1.7025 | -1.665 | -1.695 | -1.8435 | -1.801 |
| L9 | -6.9275 | -6.8 | -7.6245 | -7.5225 | -7.3525 |
| L9-DR | -1.2225 | -1.2 | -1.695 | -1.8435 | -1.2975 |
| L10 | -5.7375 | -5.61 | -6.3155 | -6.2305 | -6.086 |
| L10-DR | -1.0125 | -0.99 | -1.1145 | -1.0995 | -1.074 |
| L11 | -3.0855 | -3.0175 | -3.077 | -3.3405 | -3.264 |
| L11-DR | -0.5445 | -0.5325 | -0.543 | -0.5895 | -0.576 |

Table 3. VOLL values in different load schemes.

|  |  |
| --- | --- |
| Load | VOLL ($/MW) |
| First scheme | Second scheme | Third scheme | Fourth scheme | Fifth scheme |
| L1 | 12011.3 | 12048.3 | 12015.6 | 12016.3 | 12053.4 |
| L1-DR | 1201.13 | 1204.83 | 1201.56 | 1201.63 | 1205.34 |
| L2 | 12023.4 | 12038 | 12026.8 | 12027.4 | 12042 |
| L2-DR | 1202.34 | 1203.8 | 1202.68 | 1202.74 | 1204.2 |
| L3 | 12023.5 | 12036.1 | 12026.8 | 12023.7 | 12039.9 |
| L3-DR | 1202.35 | 1203.61 | 1202.68 | 1202.37 | 1203.99 |
| L4 | 12020.7 | 12025.8 | 12022.9 | 12023.5 | 12028.5 |
| L4-DR | 1202.07 | 1202.58 | 1202.29 | 1202.35 | 1202.85 |
| L5 | 12011.1 | 12013.3 | 12012.1 | 12012.6 | 12014.8 |
| L5-DR | 1201.11 | 1201.33 | 1201.21 | 1201.26 | 1201.48 |
| L6 | 12000.6 | 12000.6 | 12000.7 | 12000.8 | 12000.8 |
| L6-DR | 1200.06 | 1200.06 | 1200.07 | 1200.08 | 1200.08 |
| L7 | 12000.6 | 12000.6 | 12000.7 | 12000.8 | 12000.8 |
| L7-DR | 1200.06 | 1200.06 | 1200.07 | 1200.08 | 1200.08 |
| L8 | 12000.6 | 12000.6 | 12000.7 | 12000.8 | 12000.8 |
| L8-DR | 1200.06 | 1200.06 | 1200.07 | 1200.08 | 1200.08 |
| L9 | 12000.6 | 12000.6 | 12000.7 | 12000.8 | 12000.8 |
| L9-DR | 1200.06 | 1200.06 | 1200.07 | 1200.08 | 1200.08 |
| L10 | 12000.6 | 12000.6 | 12000.7 | 12000.8 | 12000.8 |
| L10-DR | 1200.06 | 1200.06 | 1200.07 | 1200.08 | 1200.08 |
| L11 | 12000.6 | 12000.6 | 12000.7 | 12000.8 | 12000.8 |
| L11-DR | 1200.06 | 1200.06 | 1200.07 | 1200.08 | 1200.08 |

Table 4. Generators active power in various load schemes

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Generator | First scheme | Second scheme | Third scheme | Fourth scheme | Fifth scheme |
| PSub-Trans(MW) | 2/91 | 3/16 | 3/498 | 4/118 | 4/369 |
| PCHP(MW) | 9 | 9 | 9 | 9 | 9 |
| PW1(MW) | 0/084 | 0 | 0/084 | 0/084 | 0 |
| PW2(MW) | 0/084 | 0 | 0/084 | 0/084 | 0 |
| PW3(MW) | 0/084 | 0 | 0/084 | 0/084 | 0 |

Table 5. Pre-determined loads to be shed and amount of f(x) in various load schemes.

|  |  |  |
| --- | --- | --- |
| Load Scheme | Pre-determined loads to be shed | f(x) ($) |
| 1 | L1-DR, L2-DR, L3-DR, L6-DR, L7-DR, L8-DR, L9-DR, L10-DR | 1799.407 |
| 2 | L4-DR, L5-DR, L6-DR, L7-DR, L8-DR, L9-DR, L10-DR | 1951.779 |
| 3 | L1, L1-DR, L3-DR, L4-DR, L5-DR, L6-DR, L7-DR, L8-DR, L9-DR, L10-DR, L11-DR | 3550.510 |
| 4 | L1, L5, L1-DR, L3-DR, L4-DR, L5-DR, L6-DR, L7-DR, L8-DR, L9-DR, L10-DR, L11-DR | 8013.048 |
| 5 | L1, L2, L3, L5, L3-DR, L4-DR, L5-DR, L6-DR, L7-DR, L8-DR, L9-DR, L10-DR, L11-DR | 10349.702 |

Table 6. Proposed UFLS procedure in various load schemes.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Minimum acceptable frequency (Hz)  | Curtailing loads (MW) | Pre-determined (MW) | Curtailing loads | Step | Power deficit (MW) | Load scheme |
| 48.282 | 1.1658 | 1.49935 | L1-DR, L2-DR, L7-DR, L9-DR, L10-DR | 1 | 2.91 | 1 |
| L8-DR | 2 |
| - | 3 |
| 47.90 | 1.6251 | 1.6251 | L4-DR, L8-DR, L9-DR | 1 | 3.16 | 2 |
| L7-DR, L10-DR | 2 |
| L5-DR, L6-DR | 3 |
| 47.811 | 1.9894 | 1.9894 | L1-DR, L3-DR, L4-DR, L6-DR, L7-DR, L9-DR | 1 | 3.5 | 3 |
| L1, L10-DR, L11-DR | 2 |
| L5-DR, L8-DR | 3 |
| 47.904 | 2.51 | 2.51 | L1, L5, L1-DR, L3-DR, L4-DR, L5-DR, L6-DR, L7-DR, L8-DR, L9-DR, L10-DR, L11-DR | - | 4.12 | 4 |
| 47.51 | 2.71 | 2.71 | L1, L2, L3, L5, L3-DR, L4-DR, L5-DR, L6-DR, L7-DR, L8-DR, L9-DR, L10-DR, L11-DR | - | 4.37 | 5 |

Table A1. Excitation system data of CHP units

|  |  |
| --- | --- |
| Parameters | Value |
| Measurement Delay (s)  | 0 |
| Filter Delay Time (s) | 0.01 |
| Filter Derivative Time Constant (s) | 0 |
| Controller Gain (pu) | 250 |
| Controller Time Constant (s) | 0.01 |
| Exciter Current Compensation Factor (pu) | 0 |
| Stabilization Path Gain (pu) | 0.01 |
| Stabilization Path Delay Time (s) | 1 |
| Controller Minimum Input | -7.5 |
| Controller Minimum Output | -7.5 |
| Controller Maximum Input | 9.35 |
| Controller Maximum Output | 9.35 |

Table A2. Governor system data of CHP units

|  |  |
| --- | --- |
| Parameters | Value |
| Speed Droop (pu) | 0.04 |
| Controller Time Constant (s) | 0.4 |
| Actuator Time Constant (s) | 0.04 |
| Compressor Time Constant (s) | 3 |
| Ambient Temperature Load Limit (pu) | 0.9 |
| Turbine Factor (pu) | 1 |
| Frictional Losses Factor (pu) | 0 |
| Turbine Rated Power (MW) | 0 |