

IMPACT OF UCTE RECONNECTION TO INTERNAL CONGESTIONS IN TRANSMISSION NETWORK OF CROATIA

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ABSTRACT

Power sector liberalization process has established new transmission control principles. Important aspects of newly liberalized market environment are known as congestion identification and management in transmission network. Congestion problem is interesting twofold: as supply security measure and market liquidity one. In this paper, congestion identification basics are presented at first. Congestions are identified with respect to total transfer capability computed from power transfer distribution factors. Then, analytical results of internal network congestions are given for a specific Croatian example. Croatian specifics are recognized in changed position of the power system (from an end part to a middle one) in states before and after UCTE reconnection. At the end, comparison of results that are obtained for two states is conducted. It numerically relates internal congestions to installed thermal capacity of ties between studied Croatian network and neighbouring ones.

KEYWORDS

Transmission network, congestions, power transfer distribution factors, UCTE reconnection

1. Introduction

Till 1988 almost all power companies in the world were vertically integrated. Generation, transmission and distribution were simultaneously controlled from a state level. Generally, transmission control responsibility was divided between national dispatching centre (generation and transmission) and regional distribution centres (distribution). As the others, Croatian power sector is currently under restructuring. Along the way, several locally specific features have appeared as a consequence of simultaneously integrated processes of restructuring and market opening. In the same time, reconstruction of two major substations at 400 kV level is expected to be completed soon. Reconnection of the 2nd synchronous UCTE zone to the main UCTE grid is under preparation.

After 12 years of isolated operation and rebuilding of major infrastructure in Croatian and Bosnian transmission networks that has been seriously damaged by the war, additional 28000 MW of load belonging to the 2nd UCTE synchronous zone will be reconnected to the main UCTE grid. The role of Croatian transmission network is found to be very important in the UCTE reconnection process. It assumes two 400 kV reconnection points and five 220 kV ones. It certainly contributes to a necessity for conducting congestion analysis of Croatian transmission network.

After reconnection of the 2nd UCTE synchronous zone to the main UCTE grid, position of Croatian transmission network is expected to change considerably. Before UCTE reconnection, Croatian transmission network is being at the border between two non-synchronized zones without any East↔West power transit possibilities. Upon reconnection, it will become a central part of South-Eastern European network with enormous expectations to satisfy various demands for power transits in these newly liberalized market conditions. Therefore, this paper presents comparison of Croatian transmission network capabilities with respect to identification of internal congestions from a viewpoint of UCTE reconnection. Congestions have not been an issue in Croatia so far. Not only that this work represents new insight over conditions of Croatian transmission network, but it also points out necessity for precise knowledge of total transfer capabilities in South-Eastern European networks. Similar analysis has been completed for the western European networks with respect to cross-border congestions [1].

2. Mathematical Background

Under normal network conditions, with all elements available, transmission system should be operated below its thermal limits. Change of injected power at single node is reflected to all of other element loadings. This kind of analysis is known as ($n-0$) analysis. In order to quantify consequences of new power transactions in ($n-0$) analysis, the concept of *Power Transfer Distribution Factors (PTDF)* is introduced through dc power flow model [2]-

[3]. The *PTDF* defines part of new active power transaction that flows through specified element.

As starting equation for ac load flow analysis, apparent power \bar{S}_i at node i is defined as

$$\bar{S}_i = P_i + jQ_i = \bar{V}_i \bar{I}_i^* = \bar{V}_i \sum_{j=1}^N \bar{Y}_{ij}^* \bar{V}_j^* \quad (1)$$

By using following substitutions

$$\bar{V}_i = V_i e^{j\Theta_i}; \bar{Y}_{ij} = G_{ij} + jB_{ij}, \quad (2)$$

the active and reactive part of the apparent power become

$$P_i = V_i^2 G_{ii} + V_i \sum_{\substack{j=1 \\ j \neq i}}^N V_j [G_{ij} \cos(\Theta_i - \Theta_j) + B_{ij} \sin(\Theta_i - \Theta_j)], \quad (3)$$

$$Q_i = -V_i^2 B_{ii} + V_i \sum_{\substack{j=1 \\ j \neq i}}^N V_j [G_{ij} \sin(\Theta_i - \Theta_j) - B_{ij} \cos(\Theta_i - \Theta_j)]. \quad (4)$$

Equation (3) represents simplified basis for a generic load flow analysis. Classical methods based on complete nonlinear ac model are not fast enough to calculate large number of different cases in reasonably acceptable time. To help solve that case, approximate linear methods are introduced. Accordingly, linear dc load flow methods are used for contingency analysis. Linear dc methods based on approximated active power equation are used for fast load flow analysis and consequently for fast real-time overload determination in the system. These methods are based on the following assumptions:

- Conductance of all transmission elements are negligible, $G_{ij} \approx 0$,
- Bus voltage angle difference across an element is smaller than 30° implying $\sin \Theta \approx \Theta$,
- Bus voltage magnitudes are kept constant ($V=1$ p.u.)

On the basis of assumptions mentioned above, load flow analysis is reduced to the active power component solely, neglecting active power loss. Equation (3) becomes first

$$P_i = V_i^2 G_{ii} + V_i \sum_{\substack{j=1 \\ j \neq i}}^N V_j [G_{ij} \cos(\Theta_i - \Theta_j) + B_{ij} \sin(\Theta_i - \Theta_j)] \approx \\ \approx V_i \sum_{\substack{j=1 \\ j \neq i}}^N V_j B_{ij} (\Theta_i - \Theta_j) \quad (5)$$

and then

$$P_i \approx \sum_{\substack{j=1 \\ j \neq i}}^N V_i V_j B_{ij} (\Theta_i - \Theta_j). \quad (6)$$

Since $V_i \approx V_j \approx 1.0$, previous expression is rewritten as

$$P_i \approx \sum_{\substack{j=1 \\ j \neq i}}^N B_{ij} (\Theta_i - \Theta_j). \quad (7)$$

Based on (7), active power P_i can be written as follows

$$P_i \approx \sum_{\substack{j=1 \\ j \neq i}}^N B_{ij} (\Theta_i - \Theta_j) = \Theta_i \sum_{\substack{j=1 \\ j \neq i}}^N B_{ij} - \sum_{\substack{j=1 \\ j \neq i}}^N B_{ij} \Theta_j = \\ = -B_{ii} \Theta_i - \sum_{\substack{j=1 \\ j \neq i}}^N B_{ij} \Theta_j = -\sum_{j=1}^N B_{ij} \Theta_j \quad (8)$$

In matrix format, it is expressed as

$$P_{\bullet N} = -B_{bus} \Theta_{\bullet N}, \quad (9)$$

where is

$P_{\bullet N}$ - bus active power vector defined as a production and load power difference ($P_{\bullet Ni} = P_{\bullet Ni}^G - P_{\bullet Ni}^L$) for all buses except the slack one,

B_{bus} - susceptance part of node admittance matrix $\bar{Y}_{bus} = G_{bus} + jB_{bus}$, or bus susceptance matrix (in the following text it is written without subscript *bus*),

$\Theta_{\bullet N}$ - bus voltage angle vector of all buses except the slack one.

By using following substitution

$$\delta_{\bullet N} = -\Theta_{\bullet N}, \quad (10)$$

equation (8) is transformed to

$$P_{\bullet N} = B \delta_{\bullet N}. \quad (11)$$

Finally, by using linear dc model the load flow analysis can be reduced to the following relations

$$\delta_{\bullet N} = B^{-1} P_{\bullet N} = X P_{\bullet N}; \Theta_{\bullet N} = -\delta_{\bullet N}. \quad (12)$$

Accordingly, the bus voltage angle change depends on the injected power change (without contingencies in the system) as it follows

$$\Delta \delta_{\bullet N} = B^{-1} \Delta P_{\bullet N} = X \Delta P_{\bullet N}; \Delta \Theta_{\bullet N} = -\Delta \delta_{\bullet N}. \quad (13)$$

Change of active power flow through element $i-j$ is connected to voltage angle change of the respective buses $\Delta P_{ij} \approx -b_{ij} (\Delta \Theta_i - \Delta \Theta_j) = b_{ij} (\Delta \delta_i - \Delta \delta_j)$.

If active power change, ΔP_k , appears at only one network bus without any contingency in the system, change of active power flow through element $i-j$ is defined as

$$\Delta P_{ij} \approx b_{ij} (X_{ik} \Delta P_k - X_{jk} \Delta P_k) = b_{ij} (X_{ik} - X_{jk}) \Delta P_k, \quad (15)$$

where X_{ik} and X_{jk} denote elements of reactance matrix X (rows i and j , column k). Generally, the *Power Transfer Distribution Factor* is defined as follows [2]-[3]

$$PTDF_{ij,k} = b_{ij} (X_{ik} - X_{jk}). \quad (16)$$

From (15) and (16), change of active power flow becomes $\Delta P_{ij} \approx PTDF_{ij,k} \Delta P_k$.

On the basis of the *PTDF*, the total change of active power flow through the element can be derived as a sum of changes of injected power at all network buses

$$\Delta P_{ij} \approx \sum_{k=1}^N PTDF_{ij,k} \Delta P_k. \quad (18)$$

In congestion analysis [4], the *PTDF* distribution factors indicate part of active power transaction from one zone to another that is taken by respective element, i.e. the *PTDF* _{ij, mn} defines part of active power transaction from zone m to zone n that is taken by transmission element from bus i to bus j

$$PTDF_{ij, mn} = b_{ij} [(X_{im} - X_{jm}) - (X_{in} - X_{jn})] \quad (19)$$

where b_{ij} denotes susceptance of transmission element between buses i and j , and X_{im} reactance matrix element defined in row i and column m . Total distribution factor of a zone connecting tie is defined as a sum of all particular distribution factors belonging to all connective elements on the tie.

Change of active power flow reflecting new active power transaction is defined as

$$\Delta P_{ij}^{NT} = PTDF_{ij, mn} P_{mn}^{NT}, \quad (20)$$

where is

i, j – incidental buses of transmission element,
 m, n – ‘from’ and ‘to’ zones where new active power transaction is realized, and
 P_{mn}^{NT} – new active power transaction.

Available transfer capability (ATC) from one zone to another could be computed by using dc load flow model through varying transaction amount until reaching specified limits. However, the *PTDF* factors are used instead to compute maximum allowed power flow significantly faster. Transaction from one zone to another results with changed power flows through all of connection ties. If transaction amount is sufficiently increased, load flows eventually reach state with at least one of the ties becoming overloaded. The transaction amount at which this happens represents the available transfer capability value between two zones.

The *PTDF* factors could be used to compute *ATC* value directly. Transaction from zone m to zone n causes change of power flow ΔP_{ij} through the element between bus i and bus j . New power flow through the element P_{ij}^N is given as a sum of initial flow P_{ij}^0 and flow change ΔP_{ij} which should be smaller than maximum limit P_{ij}^{\max}

$$P_{ij}^N = P_{ij}^0 + \Delta P_{ij} \leq P_{ij}^{\max}. \quad (21)$$

By applying *PTDF* factors in solving for transaction amount, maximum allowed power is given as

$$P_{mn, ij}^{\max} \leq \frac{P_{ij}^{\max} - P_{ij}^0}{PTDF_{ij, mn}}, \quad (22)$$

where $P_{mn, ij}^{\max}$ denotes maximum allowed transaction amount from zone m to zone n which is limited by the element between bus i and bus j .

Then, available transfer capability value ATC_{mn} between zone m and zone n is defined as a minimum among maximum allowed transaction amounts

$$ATC_{mn} = \min_{ij} P_{mn, ij}^{\max}. \quad (23)$$

In case of outage in the system, respecting power is flowing through some other paths, causing load increase on other elements. Linear dc load flow model is also useful for $(n-1)$ contingency analysis [5]-[6]. The *Line Outage Distribution Factor (LODF)* introduces a measure of active power re-dispatch in the system after outage

occurred. The *Line Outage Generator Factor (LOGF)* is highly interfered to line outage distribution factor analysis. The *Line Outage Angle Factor (LOAF)* indicates a measure of voltage angle change as a result of single outage in the system. Angle factor $LOAF_{rs}$ is used to approximate voltage angle difference between buses r and s , as a consequence of line (or generally transmission element) r - s outage. Distribution factors are also beneficial in dc switching analysis. Load flows are changed after every single switching operation. The *Line Closure Distribution Factor (LCDF)* calculates a measure of that change. Distribution factor $LCDF_{ij, rs}$ is used to approximate load flow change between buses i and j upon switching of transmission element r - z .

Available transfer capability is limited with respect to contingencies as well. The dc load flow model could be used to compute consequences of each contingency followed by application of the *PTDF* factors to find transit limitations. However, usage of the *LODF* factors makes whole procedure significantly faster. The *LODF* and *PTDF* factors could be combined to compute incremental transfer capability value with regard to the single outage. It is treated then as computation of maximum increase of transaction amount from one zone to another keeping $(n-1)$ criterion still satisfied.

If transaction between zone m and zone n and outage of the element between bus r and bus s is to be considered, then change of the power flow through the element between bus r and bus s caused by the transaction is defined as

$$\Delta P_{rs}^N = PTDF_{rs, mn} P_{mn}^N. \quad (24)$$

If there is an outage of the element between buses r and s , part of the power flow appears at the element between buses i and j . Thus, change of the power flow through the element between buses i and j due to outage of the element between buses r and s and new transaction from zone m to zone n is defined by

$$\Delta P_{ij, rs}^N = (PTDF_{ij, mn} + LODF_{ij, rs} PTDF_{rs, mn}) P_{mn}^N. \quad (25)$$

Maximum transfer from zone m to zone n limited by the element between buses i and j that occurred due to outage of the element between buses r and s is defined by

$$P_{mn, ij, rs}^{\max} \leq \frac{P_{ij}^{\max} - P_{ij}^0}{PTDF_{ij, mn} + LODF_{ij, rs} PTDF_{rs, mn}}, \quad (26)$$

where P_{ij}^{\max} denotes limitation of the power flow through the element between buses i and j after outage.

In order to determine available transfer capability with respect to single outages, it is necessary to check for all possible combinations of the outaged elements and elements with limitations, as well as steady-state power transfers

$$ATC_{mn, rs} = \min \left(\min_{ij} P_{mn, ij}^{\max}, \min_{ij, rs} P_{mn, ij, rs}^{\max} \right). \quad (27)$$

3. System Configuration

In order to determine the most congested buses/elements/areas in Croatian transmission network, several time horizon frames and system configurations have been modelled. Proposed methodology includes regional steady state dc load flow analysis. The first time horizon frame for the completion of the study was set to year 2003 as existing system state (before reconnection) and the second one to year 2005 as near future (after reconnection). Croatian transmission network is modelled at 400 kV, 220 kV and 110 kV levels, while the rest of the UCTE network (from Portugal to Greece) is modelled at 400 kV and 220 kV levels (in Greece 150 kV also). The western UCTE part (1st synchronous zone) is modelled according to official annual UCTE reports, while the model of the eastern one (2nd synchronous zone) is based on database defined in [7]. It is also assumed that all war damages in this region will be completely rebuilt and in operation. In all system configurations only winter peak loads were considered as most indicative for congestion analysis. Additional exchange scenarios East↔West are also included in the analysis. The analysis is performed for the following scenarios of Croatian power system:

year 2003:

- N3) average hydrology; import 600 MW from Hungary,
- V1) wet hydrology; no import,
- S3) dry hydrology; import 600 MW from Hungary,
- T5) dry hydrology; import 600 MW from Hungary, transit 500 MW from Bosnia (BH) to Italy,
- T6) dry hydrology; import 600 MW from Hungary, transit 600 MW from Hungary to Italy.

year 2005:

- N1) average hydrology; maximal domestic production,
- N2) average hydrology; import 800 MW from Germany and Slovakia,
- N3) average hydrology; import 600 MW from Serbia and BiH,
- V1) wet hydrology; maximal domestic production,
- V2) wet hydrology; import 800 MW from Germany and Slovakia,
- V3) wet hydrology; import 600 MW from Serbia and BiH
- S1) dry hydrology; maximal domestic production,
- S2) dry hydrology; import 800 MW from Germany and Slovakia,
- S3) dry hydrology; import 600 MW from Serbia and BiH,
- T1a) dry hydrology; import 800 MW from Germany and Slovakia, transit Switzerland (800 MW) → [Bulgaria (100 MW), Greece (700 MW)],
- T1b) dry hydrology; import 800 MW from Germany and Slovakia, transit Switzerland (1500 MW) → [Bulgaria (300 MW), Greece (1200 MW)],
- T2a) dry hydrology; import 800 MW from Germany and Slovakia, transit Switzerland (800 MW) → [Albania (300 MW), Greece (500 MW)],
- T2b) dry hydrology; import 800 MW from Germany and

- Slovakia, transit Switzerland (1500 MW) → [Albania (500 MW), Greece (1000 MW)],
- T3a) dry hydrology; import 800 MW from Germany and Slovakia, transit Bulgaria (800 MW) → Italy (800 MW),
- T3b) dry hydrology; import 800 MW from Germany and Slovakia, transit Bulgaria (1500 MW) → Italy (1500 MW),
- T4a) dry hydrology; import 800 MW from Germany and Slovakia, transit [Bulgaria (400 MW), Romania (400 MW)] → Italy (800 MW),
- T4b) dry hydrology; import 800 MW from Germany and Slovakia, transit [Bulgaria (800 MW), Romania (700 MW)] → Italy (1500 MW).

All power transit scenarios are based on the most restrictive base case (dry hydrology; import 800 MW from Germany and Slovakia).

4. Study Results

Suggested methodology applies the *PTDF* factors in base case and the *LODF* and *PTDF* factors for single outages within the "study system" (Croatia). In the "study system" total injected power should be increased for computation of maximum export capability (+50 MW) or decreased for maximum import capability (-50 MW). The power in the "opposing system" has the opposite change. The *PTDF* factors are determined to relate change of power flow through the transmission element with change of the "study system" total net interchange. Then, maximum possible power export or import should be calculated for the "study system" based on extrapolation applied over the condition that not a single transmission element is found outside allowed loading limits.

The following tables present base case and single contingencies results. In the tables, scenarios are marked by using abbreviations noted above. Total transfer capability (*TTC*) and incremental transfer capability (*ITC*) are evaluated for each scenario. Relation of those two values can be expressed as: $ITC = TTC - SNI$, where *SNI* denotes the "study system" initial net interchange. Intuitively, the *TTC* is used for the "study system" import capability, while the *ITC* for export capability. On the basis of this methodology, detailed numerical analysis is carried out to compute total and incremental transfer capabilities of Croatian transmission network [8]. By correlating findings on the distribution factors, maximum total transfer capabilities, and internal limiting critical elements, probable locations of internal congestions are identified in Croatian transmission network and evaluated from a viewpoint of UCTE reconnection.

Comparison of the results is given hereafter. At first, thermally rated total installed interconnection capacities of Croatian power system as the "study system" and neighbouring ones are presented in Table 1.

Table 1 Thermally rated total installed interconnection capacities, *TTC* (MVA)

| Interconnection | TTC (MVA); 2003 | TTC (MVA); 2005 |
|-----------------|-----------------|-----------------|
| HR-HUN | 1318 | 2636 |
| HR-BiH | 1512 | 4898 |
| HR-SLO | 4635 | 4635 |
| HR-YUG | / | 1318 |
| TOTAL | 7465 | 13487 |

Maximum power exchanges in base case for the year 2003 (with no contingency) are presented in Table 2. Table 3 presents contingency case results given for the first convergent case, which sometimes could be listed even at the 10th position in the table of critical cases. Study results for the year 2003 showed that (*n-1*) security criterion is not satisfied in the scenarios. War damages in Croatian power system are not being recovered yet. The most critical congestion points in Croatian system for import scenarios in the year 2003 are located in the north-west of Croatia (110 kV network) and transformers 220 kV / 110 kV in the south. Export scenarios are characterized by congestion points in areas Pehlin 220 kV, HPP Zakućac 110 kV and HPP Vinodol 110 kV.

Table 2 Comparison results of transmission capabilities - base case scenarios - year 2003 -

| Sc. | SNI (MW) | IMPORT | | EXPORT | |
|-----|----------|----------|----------|----------|----------|
| | | TTC (MW) | ITC (MW) | TTC (MW) | ITC (MW) |
| N3 | -607.3 | -915.1 | -307.8 | +870.2 | +1477.5 |
| V1 | -6.7 | -1115.7 | -1109.0 | +752.4 | +759.1 |
| S3 | -606.3 | -805.0 | -198.7 | +743.8 | +1350.1 |
| T5 | -605.9 | -1616.5 | -1010.6 | +238.4 | +844.3 |
| T6 | -602.8 | -636.0 | -33.2 | +544.7 | +1147.5 |

Table 3 Comparison results of transmission capabilities - contingency case scenarios - year 2003 -

| Sc. | SNI (MW) | IMPORT | | EXPORT | |
|-----|----------|----------|----------|----------|----------|
| | | TTC (MW) | ITC (MW) | TTC (MW) | ITC (MW) |
| N3* | -607.3 | -291.6 | +315.3 | -94.1 | +513.2 |
| V1 | -6.7 | -126.5 | -119.8 | -61.3 | -54.5 |
| S3* | -606.3 | -170.5 | +435.8 | -64.8 | +541.6 |
| T5* | -605.9 | -665.5 | -59.6 | -648.0 | -42.1 |
| T6* | -602.8 | -276.1 | +326.7 | -295.3 | +307.5 |

* not the most critical case, but the first convergent one

Maximum power exchanges in base case (with no contingency) for the year 2005 are presented in Table 4. Maximum power exchanges in contingency cases are presented in Table 5. Study results for the year 2005 showed that (*n-1*) security criterion becomes satisfied assuming war damages being recovered. The most critical congestion points in importing base case scenarios are located in the north-west (mainly in 110 kV network) and the south (transformation 220 kV / 110 kV). Importing contingency scenarios are characterized by critical congestions in the western 110 kV network and transformation 220 kV / 110 kV in the south. In exporting base case scenarios, congestions are located at generating nodes in the north-west and west. Similarly, critical congestion points for exporting contingency scenarios are located at generating nodes in the north-west and west.

Table 4 Comparison results of transmission capabilities - base case scenarios - year 2005 -

| Sc. | SNI (MW) | IMPORT | | EXPORT | |
|-----|----------|----------|----------|----------|----------|
| | | TTC (MW) | ITC (MW) | TTC (MW) | ITC (MW) |
| N1 | -232.5 | -2356.1 | -2123.6 | +1479.7 | +1712.2 |
| N2 | -1033.0 | -2622.4 | -1589.4 | +700.6 | +1733.6 |
| N3 | -833.1 | -2614.4 | -1781.3 | +931.0 | +1764.1 |
| V1 | -232.8 | -2414.3 | -2181.5 | +1263.2 | +1496.0 |
| S1 | -632.3 | -1889.8 | -1257.5 | +970.1 | +1602.4 |
| S2 | -1432.9 | -2342.0 | -909.1 | +245.3 | +1678.2 |
| S3 | -1232.8 | -2262.1 | -1029.3 | +624.1 | +1856.9 |
| T1a | -1432.7 | -2339.9 | -907.2 | +189.5 | +1622.2 |
| T1b | -1432.5 | -2332.3 | -899.8 | +139.1 | +1571.6 |
| T2a | -1432.4 | -2337.1 | -904.7 | +194.9 | +1627.3 |
| T2b | -1432.4 | -2325.2 | -892.8 | +149.0 | +1581.4 |
| T3a | -1432.7 | -2333.7 | -901.0 | +320.3 | +1753.0 |
| T3b | -1432.6 | -2314.6 | -882.0 | +254.0 | +1686.6 |
| T4a | -1433.4 | -2334.2 | -900.8 | +321.1 | +1754.5 |
| T4b | -1432.6 | -2314.6 | -882.0 | +260.9 | +1693.5 |

Table 5 Comparison results of transmission capabilities - contingency case scenarios - year 2005 -

| Sc. | SNI (MW) | IMPORT | | EXPORT | |
|-----|----------|----------|----------|----------|----------|
| | | TTC (MW) | ITC (MW) | TTC (MW) | ITC (MW) |
| N1 | -232.5 | -1246.7 | -1014.2 | -65.5 | +167.0 |
| N2 | -1033.0 | -1560.9 | -527.9 | -581.9 | +451.1 |
| N3 | -833.1 | -1449.0 | -615.9 | -322.8 | +510.3 |
| V1 | -232.8 | -1721.9 | -1489.1 | -87.5 | +145.3 |
| S1 | -632.3 | -935.4 | -303.1 | -411.4 | +220.9 |
| S2 | -1432.9 | -1545.0 | -112.1 | -691.7 | +741.2 |
| S3 | -1232.8 | -1380.6 | -147.8 | -423.0 | +809.8 |
| T1a | -1432.7 | -1412.8 | +19.9 | -747.5 | +685.2 |
| T1b | -1432.5 | -1516.4 | -83.9 | -798.0 | +634.5 |
| T2a | -1432.4 | -1165.8 | +266.6 | -747.2 | +685.2 |
| T2b | -1432.4 | -1461.1 | -28.7 | -788.0 | +644.4 |
| T3a | -1432.7 | -1544.1 | -111.4 | -616.3 | +816.4 |
| T3b | -1432.6 | -1541.8 | -109.2 | -768.8 | +663.9 |
| T4a | -1433.4 | -1544.5 | -111.1 | -615.4 | +817.3 |
| T4b | -1432.6 | -1541.1 | -108.5 | -753.1 | +679.5 |

Estimation of the transmission capabilities for the year 2003 base case (Table 2) results with average importing *TTC* value equal to **-1017.7 MW** (from -636.0 MW to -1616.5 MW), or **13.6%** of total installed interconnection capacity (7465 MVA). Average exporting *ITC* value equals **+1115.7 MW** (from +759.1 MW to +1477.5 MW), or **14.9%** of total installed interconnection capacity. From estimation of the contingency cases (Table 3) it is not possible to evaluate average value due to lack of convergence of the first critical element. For the year 2003, (*n-1*) criterion is not satisfied with respect to *TTC*.

Estimation of the transmission capabilities for the year 2005 base case (Table 4) results with average importing *TTC* value equal to **-2342.2 MW** (from -1889.8 MW to -2622.4 MW), or **17.4%** of total installed interconnection capacity (13487 MVA). Average exporting *ITC* value equals **+1675.6 MW** (from +1496.0 MW to +1856.9 MW), or **12.4%** of total installed interconnection capacity. Estimation for the contingency cases (Table 5) results with average importing *TTC* value equal to **-1437.8 MW** (from -935.4 MW to -1721.9 MW), or **10.7%** of total installed interconnection capacity.

Average exporting *ITC* value in contingency cases equals **+578.1 MW** (from +145.3 MW to +817.3 MW), or **4.3%** of total installed interconnection capacity.

Previously discussed results are showed in Tables 6 and 7. It is necessary to bear in mind that the average values represent only rough estimation given for relatively small number of cases that also have different characteristics with regard to power plant engagements. Rather large deviations from the average values occur sometimes. This should be carefully taken at the evaluation of total transmission capabilities, especially in contingency cases.

Table 6 Average transmission capabilities – base case -

| year | IMPORT | | | | EXPORT | | | |
|-------|----------|---------|----------|----------|----------|---------|----------|----------|
| | TTC (MW) | TTC (%) | MIN (MW) | MAX (MW) | ITC (MW) | ITC (%) | MIN (MW) | MAX (MW) |
| 2003. | -1017.7 | 13.6 | -636.0 | -1616.5 | +1115.7 | 14.9 | +759.1 | +1477.5 |
| 2005. | -2342.2 | 17.4 | -1889.8 | -2622.4 | +1675.6 | 12.4 | +1496.0 | +1856.9 |

Table 7 Average transmission capabilities – contingencies -

| year | IMPORT | | | | EXPORT | | | |
|-------|----------|---------|----------|----------|----------|---------|----------|----------|
| | TTC (MW) | TTC (%) | MIN (MW) | MAX (MW) | ITC (MW) | ITC (%) | MIN (MW) | MAX (MW) |
| 2003. | / | / | / | / | / | / | / | / |
| 2005. | -1437.8 | 10.7 | -935.4 | -1721.9 | +578.1 | 4.3 | +145.3 | +817.3 |

Basic characteristics of Croatian transmission system that are recognised with respect to the congestion analysis could be found in severed 2003 shape and in different import and export transmission capabilities for the year 2005. In Croatian power system, generating sources are dominantly connected at 110 kV and 220 kV voltage level. Accordingly, exporting congested paths are located dominantly in nearby 110 kV and 220 kV network. Similarly, power import is mostly realized through 400 kV and 220 kV network. On its way down to consumption at lower voltage levels, it causes congestions at 220 kV / 110 kV transformations. Generally, new generating sources are connected at 400 kV voltage level should power system be export-orientated. Power systems that are more import-orientated should develop not only 400 kV network, but all transformations on its way down to consumption at lower voltage levels as well. Power systems with strong 400 kV network and weak transformations are committed to power transits solely.

Evaluation of total transmission capabilities are here methodologically directed toward identification of internal congestions. It enables better overview of domestic transmission facilities needed from power system planning perspective. However, congestion analysis could be conducted for cross-border connecting ties in real time. From operational perspective, computation of the *TTC/ITC* values is needed on-line for each connecting tie of the "study system" to neighbouring ones. Then, larger number of different cases could be recognised (engagement of power plants, interchanges, transits) enabling their statistical analysis better shape. Moreover, impact of each individual transaction to total transmission capabilities could be evaluated in real time.

5. Conclusions

This paper presents basics of congestion analysis and results obtained for specific situation of Croatian transmission network with respect to UCTE reconnection. On the basis of dc load flows, the distribution factors are computed for base case and single contingencies. By using distribution factors, maximum total import/export transmission capabilities are determined with respect to limiting critical elements inside of Croatian transmission network (400 kV, 220 kV and 110 kV). Combined findings on the distribution factors, total transmission capabilities, and internal limiting critical elements, possible congested paths are identified from planning perspective. The UCTE reconnection significantly improves transmission capabilities of Croatian network.

6. References

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