Spares strategies for transformers and transmission plant

Earlier articles have described how the use of major strategic spare components can improve the availability of large turbogenerators and experience of this strategy in the United Kingdom electricity supply industry. This article outlines the complementary strategies which have been adopted for generator transformers and transmission plant. Applications in respect to transmission transformers, switchgear and circuit and other substation equipment are described. The mutual advantages arising from sharing arrangements and co-operation on the basis of these strategies by the United Kingdom mainland generating boards is noted

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An earlier article in this Journal[1] described the development by the CEGB of a spares strategy for generator components and the use of these spares in improving generating plant availability. A paper, presented in October 1988 to the Institution of Mechanical Engineers,[2] described the complementary strategy for turbine components with the same objectives.

Over the same period the CEGB also developed spares strategies for transformers and other transmission equipment aimed at achieving similar economic improvements in transmission plant availability. This article outlines these strategies and some of the considerations which led to their development over the years.

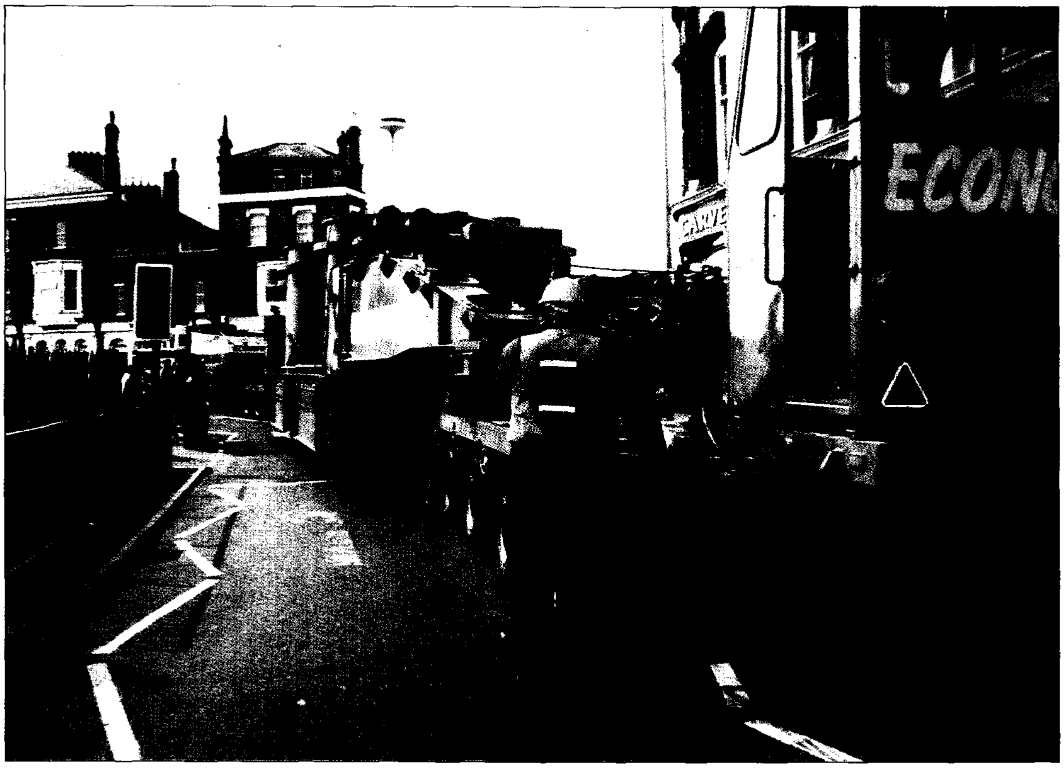
Generator transformers

For many years virtually all main generators have been directly connected to the UK Grid or Supergrid systems via generator transformers. As a result, each of these generator transformers forms an integral element of its associated generating unit. Consequently the generating unit availability is directly affected by failures of the generator transformer or any need for off-load maintenance on it. Thus the economic justification of a proposal to hold a strategic spare for a family of generator transformers can be assessed in exactly the same way as proposals to hold generator components as described in the previous article.[1]

The strategy of holding spare generator transformers essentially began at the same time as major spares for the turbogenerators, i.e. as the 500 MW units were being developed. However, unlike the turbogenerators, the designs of generator transformers did not fall neatly into the same four families. This was principally due to the Supergrid connections being, according to location, some at 275 kV and others at 400 kV. There were also some slight differences in rating, some being rated at 570 MVA whilst others, especially the later units, were 600 MVA.

However, unlike turbine or generator components, which have to be fitted to close mechanical tolerances, the mechanical connections of a transformer are far more flexible or adaptable. Oil and cooling water pipework can be rerouted or adapted with relatively little effort and requiring very little time. Similarly, the primary and secondary electrical connections can be adapted readily. It has therefore been found that a generator transformer can be replaced by one of a different design, even one from a different manufacturer, provided that its electrical characteristics are similar. Its rated voltages must clearly be matched: in practice this only relates to the secondary voltage as most 500 MW units generate at a standard 22 kV. More flexibility is possible with regard to impedances and rating, and interchanges between 570 MVA and 600 MVA units have successfully taken place.

Initially, the design concept for the nationally held spare generator transformers was based on a strategy of 'loan' units, i.e. when a transformer failed in service, it would be replaced by a loaned spare while it was repaired. On completion of the repair, it would be replaced in its original location and the loaned unit returned to its storage site to await a further failure. As a result of this concept, it was assumed that the spares would be used infrequently and for limited durations. Accordingly, the design of the spare transformers could be optimised differently from that of the dedicated installed units and some desirable, but not essential, operational features could be omitted. One of the known problems with these large transformers was that of weight: for the installed units this was very close to the limitations imposed on road access routes between the manufacturer's works



One of the spare Grid transformers in transit

and the power station sites. This applied even if sea transport and specialist air cushion road transporters were used as far as possible. In the design of two of the early spare transformers, weight was reduced, in one case by adopting a 'high-loss' design, and in the other by sacrificing the on-load tapchanger.

As experience with the 500 MW units built up, the numbers of failures and other circumstances requiring attention to the generator transformers, such as the need for modifications, became significant. This led to a reappraisal of the strategy. It became very evident that the 'loan' strategy was resulting in twice as many transport moves, site works and unit outages as would have been necessary with a 'fit and forget' strategy as practised with generator stators. The resultant costs were also greatly increased. It was therefore decided that for the future a change would be made towards a 'fit and forget' strategy.

All the power stations with 500 MW units, except one, were supplied with generator transformers of the single-tank three-phase type. Experience has shown that in most cases of internal faults, contamination has spread from the faulty phase to the other two phases such that a complete rewind of all three phases has been necessary. This has resulted in the costs of repair being only marginally less than the cost of a replacement transformer. Even this differential can be significantly reduced if, by purchasing a replacement, transport of the failed unit is obviated. However, the need to investigate a fault often prevents such economic alternatives being fully exploited.

While the 'loan' strategy was still current and failure rates were expected to be low, a 'dual-ratio' spare was ordered to provide cover for two groups of generator transformers. This could be deployed to a 500 MW unit connected to the 400 kV Supergrid or to a smaller unit which had a generation voltage of 18·5 kV and was connected to the 275 kV system. The CEGB had a number of such units with capacities ranging from 200 to 350 MW. While this spare has been usefully deployed on a number of occasions, a direct 'fit and forget' spare is preferred nowadays if one is available.

Economic cases for spare generator transformers

In common with all proposals to hold major strategic spares, spare generator transformers are only held when justified by a rigid economic appraisal based on the risks to system operation costs. The method is essentially the same as described in the previous article.[1] However, in the case of generator transformers there was concern that the value of p, the probability of a unit requiring a spare, derived from historical records, could be distorted by failures arising in either the 'infant mortality' or 'wear out' phases. To ensure that these were discounted a more sophisticated analysis was carried out into the failures that had taken place in the transformer family concerned.

This analysis is based on the total operating hours to failure. It also assumes that, when a transformer is repaired, because it is invariably rewound, it is essentially a new transformer and therefore starts a new life. The life experienced by transformers which have not failed is also taken into account by treating such 'survivors' in the same way as in the statistical treatment of incomplete life testing of metallurgical specimens. Lives to failure are then plotted against the corrected cumulative percentage of the population that has failed, on Weibull paper. The resultant graphs clearly identify the various phases of the 'bathtub' curve. An appropriate value of p for use in the economic model can be readily obtained by taking, for each member of the supported family, a value from that part of the graph in which its future running is expected to fall.

Analyses of this type were carried out for the older 100 and 120 MW units connected at 132 kV as well as for the larger units. For this family, spares were obtained from redundant plant being scrapped. The graph for this family did, however, show a distinct upturn, presumably due to the onset of a 'wearout' phase, at lives exceeding about 15 years. A similar upturn in the case of the 500 MW 400 kV transformers has not been clearly recognisable, although some units, at the time of the last analysis, had exceeded 10^5 running hours.

The early Weibull analyses of generator transformer failures had to be carried out using 'calendar time installed' as the measure of exposure time. This was dictated by the ready availability of this information rather than by logic. When this basis was used in the initial analysis of the 500 MW 400 kV family, the different running regimes of the coal-fired and oil-fired plants made this approach somewhat suspect. Fortunately, for these larger units, the records of running hours were more readily available and this measure of 'exposure time' was used in later analyses.

The two most significant parameters likely to influence the transformer lives to failure were felt to be the time subjected to electrical stress and heat loadings integrated with time. In practice the time the unit was running connected to the system would be a direct measure of the time the transformer was subject to electrical stress. As far as heat loading is concerned this would essentially be a measure of the MVA throughput or the heat losses or a combination of these. Because large machines are normally run at or near full load while on the system or are shut down when they become 'out of merit', this 'heat loading function' will tend to be roughly constant while the unit is generating and zero in value when the unit is off load. Thus the integral of this 'heat function' will sensibly be proportional to the unit 'running hours' as in the case of the other parameter. In view of this, the use of 'running hours' as a measure of 'exposure time' appears to be justified.

Supergrid transformers

Interconnections between the 400 kV and 275 kV Supergrid systems and between both of these, and the Area Board and residual CEGB 132 kV systems are by means of transmission transformers. Failures of these transformers have occurred, albeit with modest failure rates. These failure rates have generally been of the same order as those reported in recent CIGRE international survey reports. Nevertheless, the large numbers of transformers involved justify the holding of spare transformers. For example there are about 90 transformers connecting the 400 and 275 kV systems.

As in the case of generator transformers, the flexibility of mechanical and electrical connections will normally permit a spare to be of different design from that of the failed unit it is to replace, within certain limits. This is aided by the large measure of standardisation that has been applied to the design of transformer components and to a lesser extent to the transformer designs themselves. The only critical factor is the voltage ratio. Generally impedances are only marginally different for similarly specified transformers and do not pose a problem in most instances. Furthermore, again within certain limits, a transformer can be replaced by a spare of a different rating, normally by one of higher capacity. This allows a spare 1000 MVA 400/275 kV autotransformer to provide cover for similarly rated transformers and also 750 MVA and 500 MVA units of the same voltage ratio. Physical space is seldom an insuperable restraint.

Although most transformers have electrical connections of the 'open' type, using air insulated bushings, a few may differ. Some may have cable boxes, especially on the LV side while, in recent years, a number have been directly connected to SF_6 filled metalclad switchgear. Whenever possible, the spare transformers are designed to be adaptable to enable them to be deployed to any such abnormal situations in the family for which they are to provide strategic cover. In these circumstances the adaptation kits are held in store to complement the spare transformer when needed. Where direct adapation is not provided, the possibility of a 'jury-rigged' adaptation using, for example, spare sealing ends, is expected to be practicable. Spares of these components are already held against failures of similar components in service and thus the adaptation of the transformer spares strategy is often the most economic method of achieving strategic cover for such situations.

Failure of any single transformer on the transmission system can usually be accommodated with, at worst, an interruption of supply to consumers lasting only minutes. If there are no parallel feeds in the Supergrid or Grid system itself, distribution system interconnections usually exist. It is therefore impossible to ascribe financial loss to any single transmission transformer failure, unlike the case of generator transformers described earlier. However, there is a loss in respect to system security. System security in the United Kingdom is covered by rules which are applied to both system design and system operation. These rules are based on practical experience of achieving an acceptable standard of continuity of supply to customers. As far as the author is aware there has been no direct correlation of these standards to economics.

It follows therefore that economic justifications cannot be made for proposals to hold spare transmission transformers in the way that is normal for generation spares. Essentially a decision has to be made based on 'engineering judgment'. Nevertheless, the relative merits of schemes can be assessed on the grounds of reliability or availability criteria and the results of such assessments used to assist in the judgments to be made. One approach, advocated in a paper by Sahu to the American Power Conference in 1980,[3] suggested that sufficient spare transformers should be held available to meet annual demands in all but 15% of years. Although this approach was considered, it has the disadvantage of failing to directly address the plant availability which has the greatest influence on system security.

In the event of a transformer failure, there will be some downtime. If a spare is immediately available this will be a minimum, limited to the time required to remove the failed unit and to erect and commission the replacement. If no spares are held, the downtime is extended either by the time to repair the failed unit or by the lead time for a purchased replacement. In either case this could be 12 to 15 months. When spares are held, these will immediately cover some failures but other failures will arise while the stock is temporarily exhausted. The net increase in downtime, over the minimum described above, represents an availability loss which is 'controllable' according to the number of spares normally stocked. The degree of cover offered by a stock of '*n*' spare transformers for a population of '*N*' installed units can be indicated by an availability factor calculated from

$$1 - \frac{\text{average controllable downtime achievable with } n \text{ spares}}{\text{average controllable downtime with no spares held}}$$

This factor is normally expressed as a percentage value.

Both the numerator and denominator of the above expression can be determined using the same approach as described for the economic justification of generator spares in Reference 1. Schemes for additional transformers spares for the CEGB have been presented accompanied by a calculation of the availability factors that would exist for the family concerned with and without the proposed additional spare transformer. Although the final decisions are based on 'engineering judgments', proposals have generally been successful unless the existing 'availability factor' has exceeded 90 or 95%.

EHV switchgear

When the 275 and 400 kV Supergrids were first erected in the United Kingdom, most of the switchgear installed was of the air-blast type. Meanwhile the earlier 132 kV systems had a mixture of air-blast and oil-break units.

Initially some strategic national cover was provided for the air-blast supergrid units from stocks of replacement subassemblies. The subassemblies stocked were predominantly those which were found to require most frequent attention such as the interrupter units. In the light of a number of serious switchgear failures additional subassemblies were stocked such that, for some designs of circuit breaker, enough subassemblies were held to be able to reconstruct a complete phase or, in a few cases, a complete circuit breaker in the event of a major mishap.

Spares for the 132 kV circuit breakers were mainly held locally rather than on a national basis, especially after the greater part of the 132 kV system was transferred to the Area Boards and out of CEGB control.

By the early 1980s a number of circuit breakers had been installed at all three voltage levels based on SF_6 interrupers. Some of these installations were of the 'metalclad' type while others were in 'open' type substations. The 'metalclad' installations included some associated with large new generating units while others were destined for use in conjunction with the new cross-Channel connection with Electricité de France. Clearly such installations had a significant economic status as well as the normal security implications of transmission equipment. It was therefore decided that the 'metalclad' designs should be given strategic cover with all major subassemblies stocked. These included interrupters and associated disconnector subassemblies.

The philosophy adopted for the initial stocking was based on the spares being called on for two distinct reasons. The first was to cover for a major fault. It was assumed that, although this was most likely in the interrupter or disconnector sections, it could occur in any of the enclosed sections but, as a result of the phase segregation, was only likely to affect one phase. This required a stock for one phase only of all the various subassemblies involved. The second call upon spares was expected to be in support of an overhaul of a circuit breaker, especially a generator circuit breaker. It was felt that this would be achieved by subassembly exchange and then refurbishment of displaced units 'off-line'. To cover this type of call, the stock would be held at sufficient level, for the subassemblies concerned, sufficient for a complete breaker, i.e. for all three phases.

The total stock for metalclad designs therefore comprises these two elements of stock added together.

At about the same time as spares for 'metalclad' designs were being considered, the manufacturers of the HV switchgear indicated that they now considered the air-blast and oil-break designs as obsolescent if not obsolete, in the light of developments with SF_6 designs. In the light of this, it was appreciated in the CEGB that future spares, required to support existing circuit breakers, were likely to become more expensive or with increased lead times or both. As a result, a complete rethink of the overall spares strategy and maintenance strategies was initiated.

The compactness of the modern 'open-type' SF_6 circuit breakers compared with the earlier, equivalently rated air-blast units was recognised at an early stage. Follow-up studies confirmed that virtually all air-blast units could be replaced by SF_6 modern units. A similar strategy for oil-break units was considered but, in the case of these units, additional space to accommodate post type current transformers, to replace those mounted in the oil breaker bushings, can cause difficulties.

Spares held for the various air-blast and oil-break circuit breakers were held both to cover major failures and also to expedite overhauls by subassembly exchange, as described for the metalclad units earlier. This latter need will, of course, persist as long as these pre-SF_6 designs remain in service.

The strategy for circuit breakers has therefore developed as follows. A strategic stock has been purchased of complete SF_6 circuit breakers for all three voltage levels. These will be deployed either to replace any similar SF_6 circuit breaker that fails or to replace any obsolete design that suffers a serious failure. Existing stocks of subassemblies for air-blast or oil-break units will continue to be used to cover minor failures or overhaul requirements. When such subassemblies become too worn or damaged to be refurbished they will have to be scrapped but, because they are obsolete, they cannot be replaced, as hitherto, by purchasing new spares from the manufacturer. Instead, when stocks reach a minimum level, a nominated breaker of the affected design will be replaced by an SF_6 unit from the spares pool and then cannibalised and parts refurbished to restore stock levels. The exchange can be arranged to take place at a convenient outage. The stock of subassemblies will also receive any salvaged subassemblies from a major circuit breaker mishap which can be satisfactorily refurbished.

To support this strategy, two actions have already commenced. First the existing numbers and types of obsolete circuit breakers installed in the CEGB and the SSEB and, in the case of 132 kV units, in the Area Boards have been surveyed. Secondly, preliminary design studies have been carried out to identify the work necessary and the materials required to replace any obsolete design circuit breaker by one of the equivalent SF_6 spares held in stock. Where special materials or equipment, such as current transformers as described above, are identified, it is intended that these be held to supplement the stocks of circuit breakers themselves.

Spares for transmission circuits

In the United Kingdom, the vast majority of transmission circuits are by overhead lines. However, some cable circuits have been installed and, as in the case of the North London 275 kV ring, these are usually important in terms of system security. Accordingly strategic stocks of cables of the types used in these important circuits have been held, either since they were installed or very soon afterwards. Components for both stop joints and through joints for these cables are also held. These are used either as spares for existing joints which suffer failures or to enable a short section of cable to be inserted, should a cable suffer mechanical damage. Such mishaps tend to be more prevalent than failures in the cables themselves. Over the years a number of special cables have been installed, notably in tunnels such as the ones under the River Severn and those leading to the pumped storage generating station at Dinorwig. Lengths of spare cable suitable for these special but important circuits are also held against the need to repair any future failures. This is a necessary response in the light of the exceptional lead time that would exist for the manufacture of these specific cable designs.

As far as overhead line circuits are concerned, limited stocks of conductors, insulators and fittings are held on a local basis for normal repair and maintenance work. These would be quite inadequate to deal with a major failure. Forward ordering of these materials for refurbishment work on the system provides stocks of strategic spares for all line constructions although some substitution would be necessary. Total tower failure is far less common and normally results from extreme weather conditions generally combined with structural weakening resulting from long-term dynamic loading conditions. Tower collapse is likely to cause damage to the foundation steelwork and rebuilding cannot be completed in an acceptably short time scale. The strategy adopted is to provide equipment for temporary line deviations around the damaged tower using temporary stayed structures to allow re-energisation of the circuits. A strategic stock of selected towers and extensions is held at fabricators' works, and this stock is 'rolled over' as structures are ordered for new construction work. The strategic stock of towers was compiled taking account of the historical frequency of tower failures, the population of towers of a particular design and type and the number of towers likely to be damaged in a single incident. The bulk of transmission towers on the systems are constructed of imperial dimension rolled steel sections. Replacement stocks are of metric steel sections giving an added requirement for adaptor plates to connect metric to imperial sections.

Another source of potential damage to overhead lines arises from aircraft crashes. To date, only light aircraft have been involved and thus damage to towers in such incidents has been limited and well within the scope considered for abnormal weather risks.

Other substation equipment

Apart from Grid transformers and switchgear, already discussed, strategic spares are held nationally for other items of substation equipment. These include current transformers and both wound and capacitor voltage transformers. Spares for both post and underslung insulators are held but, in view of their relative freedom from damage, it has been deemed unnecessary to hold spares for busbars themselves or support structures. For substations with air-blast switchgear, major spares for the high-pressure air compressors are held and these constitute a large proportion of the releases made from the central store.

Sharing with Scottish Boards

As described in the earlier articles[1,2] a formal arrangement has been in existence for several years under which the CEGB, the SSEB and the NSHEB share certain of the higher value spares such as transformers. The arrangement also provides an agreed basis for mutual support where one Board holds a spare needed by another, but this has not been purchased jointly. This co-operation, which has operated to the benefit of all three Boards, extends to the spares discussed in this article.

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